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Notes

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Abstract: Basin modelling tools are now more efficient to reconstruct palinspastic structural cross sections and compute the history of temperature, pore-fluid pressure and fluid flow circulations in complex structural settings. In many cases and especially in areas where limited erosion occurred, the use of well logs, bottom hole temperatures (BHT) and palaeo-thermometers such as vitrinite reflectance (Ro) and Rock-Eval (Tmax) data is usually sufficient to calibrate the heat flow and geothermal gradients across a section. However, in the foothills domains erosion is a dominant process, challenging the reconstruction of reservoir rocks palaeo-burial and the corresponding calibration of their past thermal evolution. Often it is not possible to derive a single solution for palaeo-burial and palaeo-thermal gradient estimates in the foothills, if based solely on maturity ranks of the organic matter.

Alternative methods are then required to narrow down the error bars in palaeo-burial estimates, and to secure more realistic predictions of hydrocarbon generation. Apatite fission tracks (AFT) can provide access to time–temperature paths and absolute ages for the crossing of the 120 °C isotherm and timing of the unroofing. Hydrocarbon-bearing fluid inclusions, when developing contemporaneously with aqueous inclusions, can provide a direct access to the pore-fluid temperature and pressure of cemented fractures or reservoir at the time of cementation and hydrocarbon trapping, on line with the tectonic evolution. Further attempts are also currently made to use calcite twins for constraining reservoir burial and palaeo-stress conditions during the main deformational episodes. Ultimately, the use of magnetic properties and petrographical measurements can also document the impact of tectonic stresses during the evolution of the layer parallel shortening (LPS).

The methodology integrating these complementary constraints will be illustrated using reference case studies from Albania, sub-Andean basins in Colombia and Venezuela, segments of the North American Cordillera in Mexico and in the Canadian Rockies, as well as from the Middle East.

Present geothermal gradients can usually be derived from BHT (bottom hole temperature) measurements. Seemingly, the overall distribution of conductivities in the overburden can be reasonably described by applying standard values for each dominant lithology, provided the latter can be properly documented by means of well logs and extrapolated laterally by the use of seismic sequences and attributes. In nearshore segments of passive margins and in foreland basins, where lithosphere

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and crustal thickness remained relatively constant and only limited erosion occurred, vitrinite reflectance (Ro) and Rock-Eval (Tmax) values measured along vertical profiles (i.e. geochemical logs in wells) are usually sufficient, when combined with 1D well modelling (burial v. time curves), to derive realistic values for the palaeo-thermicity of a given area.

In contrast, calibration of petroleum modelling becomes more complex in areas where both crustal and lithosphere thickness have been strongly modified since the deposition of the source rock, either in the distal portion of continental margins near the continent–ocean transition or in the inner parts of the orogens, where slab detachment or asthenospheric rise could result in drastic changes in the heat flow. Large uncertainties are also recorded when addressing petroleum modelling in foothills domains, basically because of the lack of controls on the palaeo-burial estimates in areas which have been strongly affected by erosion, and where it becomes challenging to solve for each time interval and for each cell of the model two unknown parameters (i.e. both temperature and burial).

This paper will first briefly describe the current state of the art and integrated workflow developed recently for addressing basin modelling in fold and thrust belts (FTB). It will then document, based on representative case studies, the use of various palaeo-thermo-barometers for reducing the error bars in petroleum modelling in such tectonically complex areas as FTB, where major erosional events prevent any direct access to the palaeo-burial.

Integrated workflow developed for hydrocarbon and pore-fluid pressure modelling in FTB

Dewatering processes and coeval overpressures build up have been widely documented in modern accretionary wedges by means of seismic attributes and deep ODP–IODP (International Oceanic Drilling Program) wells. For instance, the increasing load of synflexural sediments deposited in foredeep basins results in a vertical escape of formation water and a progressive mechanical compaction of the sedimentary pile where pore-fluid pressures remain dominantly hydrostatic. However, this process ultimately induces a velocity increase of seismic waves from the surface down to a depth where the vertical permeability reaches a minimum, precluding any further escape of underlying fluids toward the seafloor. Undercompacted sediments occur beneath this compaction-induced regional seal, being characterized by slower seismic velocities and overpressures. Worth mentioning, this occurrence of an overpressured horizon in the foreland strongly decreases the mechanical coupling and friction between deeper and shallower horizons, thus helping the localizing and propagating forelandward of the deformation front.

Although FTB share many similarities with offshore accretionary wedges in terms of the modes of thrust emplacement and overall structural style, boundary conditions of these two geodynamic systems are rather different in terms of porosity/permeability distributions and fluid flow regimes. This is due to (1) the age of the accreted series (usually restricted to the relatively young synflexural sequences in accretionary wedges, against dominantly pre-orogenic passive margin sequences in FTB), and (2) the origin of the fluids (mixing of sedimentary fluids with meteoric water in FTB, against entirely marine or basinal fluids in offshore accretionary wedges).

Unlike in modern accretionary wedges, overpressures can usually not be detected by anomalies in the seismic attributes in FTB, making integrated basin modelling techniques an indispensable tool, as documented below, to predict the distribution of pore-fluid pressures and hydrocarbon (HC) potential before drilling.

Coupled kinematic, thermal and fluid flow modelling in the frontal part of Eastern Venezuelan FTB

The El Furrial and Pirital thrusts developing at the front of the Eastern Venezuelan thrust belt have been the focus of a pilot modelling approach coupling various 1D (Genex) and 2D (Thrustpack and Ceres: Sassi and Rudkiewicz 2000; Schneider *et al.* 2002; Schneider 2003; Deville & Sassi 2006) basin modelling tools.

A structural section was first compiled from the interpretation of seismic profiles, and integration of wells and outcrop data. This section was then balanced and restored to its pre-orogenic configuration, providing an accurate control on the initial spacing of future thrusts. Incremental 2D forward kinematic modelling coupling erosion/sedimentation and flexure was subsequently performed with Thrustpack by means of a trial and error process, until the result section of the model was consistent with (1) the present architecture of the El Furrial and Pirital thrusts, (2) the pattern of erosional surfaces and unconformities currently observed in the Morichito piggyback basin and adjacent Pirital High, as well as (3) the measured temperature proxies (Ro from wells and outcrops).

Despite strong erosion on top of the Pirital allochthon, where late Miocene and Pliocene series of the Morichito thrust-top basin rest locally directly on top of Cretaceous series (Fig. 1), this thrust unit

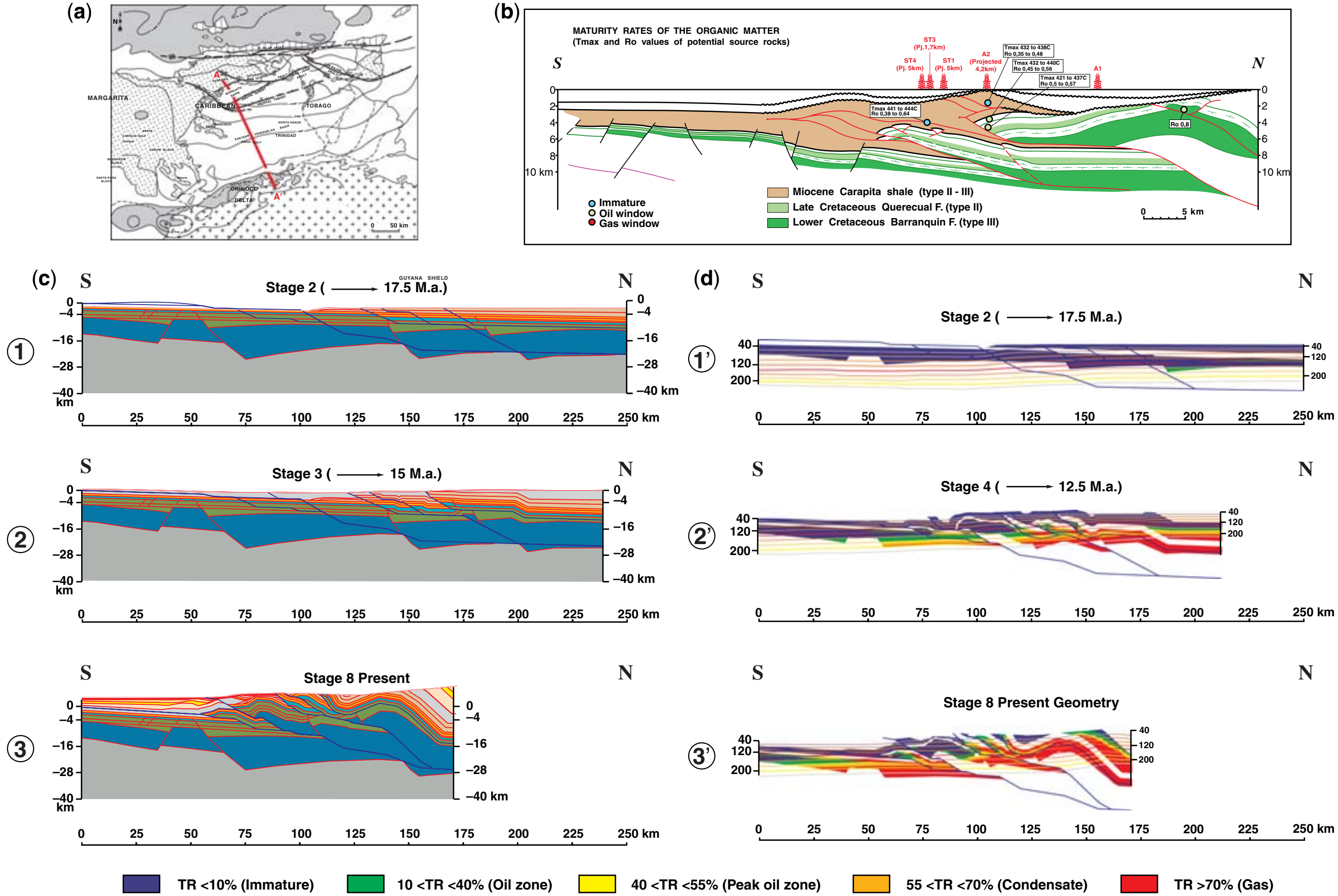

Fig. 1. 2D forward kinematic and petroleum modelling along a regional transect in Eastern Venezuela. (**a**) Location map; (**b**) Structural section across the El Furrial and Pirital structures, outlining the BHT and maturity indicators (Tmax and Ro) used for calibration; (**c**) Left column: Main stages of the kinematic modelling. Blue: Jurassic = synrift; green = Lower Cretaceous (Barranquin Formation); deep green: Querecual source rock; orange: Naricual Ologocene reservoir; brown, grey and yellow: Miocene Carapita Formation, La Pica and Morichito Pliocene formations. (**d**) Right column: Transformation rates of the main potential source rocks for the same time intervals.

is adjacent to the El Furrial trend where a continuous Palaeogene and Neogene sequence is preserved. Because the Pirital allochthon is also close enough to the Maturin Basin, where the entire passive margin and flexural sequences remained undeformed, basal heat flow was assumed to always have been constant along the entire transect; that is, heat flow values derived from 1D Genex modelling in wells from the foreland and El Furrial trends could be extrapolated laterally along the entire profile for the 2D Thrustpack and Ceres modellings. This assumption results in a good agreement between observed and computed values of Tmax and Ro, the Upper Cretaceous Querecual source rocks being indeed overmature in the Serraña (allochthon), but still in the oil window in the footwall of the Pirital thrust, whereas the Miocene Carapita shales are still immature within the El Furrial anticline (Fig. 1).

The intermediate geometries of the Thrustpack structural model were ultimately used as input data for the 2D Ceres pore-fluid pressure and fluid flow modelling. Pore-fluid pressures in the wells document a currently overpressured regime in the Oligocene Naricual sandstone reservoirs of the El Furrial trend, which are indicated by a white circle in Figure 2. These pressure values, amounting up to 80 MPa at depths between 4 and 5 km in the Oligocene reservoirs (Fig. 2c), were used for quality control of the modelling.

Apart from confirming the HC potential of this part of Eastern Venezuela, this pilot modelling sequence provided useful information on the timing and boundary conditions for pore-fluid pressure building along the transect, as well as on the history of fluid flow velocity within the Oligocene reservoir of the El Furrial trend:

(1) According to the model, overpressures in El Furrial reservoirs did not start until the structural closure was effective on both sides of the anticline, all compaction water previously escaping laterally toward the south, updip of the foreland flexure. However, this result is probably biased by the fact the litho-stratigraphic description of the geological section was oversimplified. In particular, neither lateral sedimentological nor porosity/permeability variations were taken into account here when describing the regional internal architecture of the Oligocene and Neogene series. Most likely, the integration of an additional step in the modelling, involving the forward simulation of the sedimentation pattern and lithofacies with Dionisos or coeval sedimentological tools (Granjeon & Joseph 1999), would have introduced further controls on lateral changes in sand v. shale ratios, which are likely to occur in the foreland autochthon. This would probably have accounted for the development of lateral permeability barriers in the foreland, which could indeed preclude or at least delay the lateral escape of compaction water, and help generate overpressure in the Oligocene reservoirs in the foreland autochthon before the complete structural closure of El Furrial.

(2) The Oligocene reservoirs of El Furrial trend behaved as a relatively closed system (0 value for the velocity of the fluids) until the onset of the foreland flexure development. Seemingly, these reservoirs have been again totally isolated (closed systems) since the time an effective structural closure had developed on both sides of this anticline. Between these two stages, the Ceres results indicate a short episode of active foreland-directed fluid flow in El Furrial reservoirs. This squeegee episode (e.g. Machel & Cavell 1999) occurred when the reservoirs were still connected with the foreland, in the footwall of active thrusts. Alternatively, vertical escape of El Furrial fluids toward the Pirital allochthon was apparently possible at the time Oligocene series of both compartments were still connected (Figs 2 & 3a). Further evidence that the Pirital thrust was episodically a conduit accounting for a vertical escape of the fluids is attested by the occurrence of (1) HC accumulations (mostly heavy biodegradated oil) in the Pliocene sedimentary infill of the Morichito thrust-top basin, which result from a remigration from deeper reservoirs, and (2) hydrothermal circulations and lateral escape of hot fluids along the basal unconformity of the Morichito basin, as indicated by hot springs and high temperature (Th) in the fluid inclusions of quartz cements within the Pliocene Morichito sandstones (Bordas-Le Floch 1999).

Topography-driven fluid flow v. tectonically induced squeegee episode of fluid expulsion in FTB

Apart from the poor description of lateral variations in the sand v. shale ratios of Cenozoic series, other limitations of the Ceres basin model result from its current lack of horizontal compaction. As it stands, the values of the overpressures computed by Ceres are dominantly controlled by the hydraulic heads (i.e. the topography of the hinterland) and by the capillary pressure barriers. However, as discussed below, one of the major processes operating in both modern accretionary wedges and active FTB is the layer parallel shortening (LPS), which stimulates the pressure-solution mechanisms, inducing lateral changes in the compaction, decrease in porosity and permeability, and coeval increases in the seismic velocities. Most likely, LPS contributes a lot to the development of overpressures and tectonically controlled squeegee episode of forelandward expulsion of compaction water (Nieuwland *et al.*

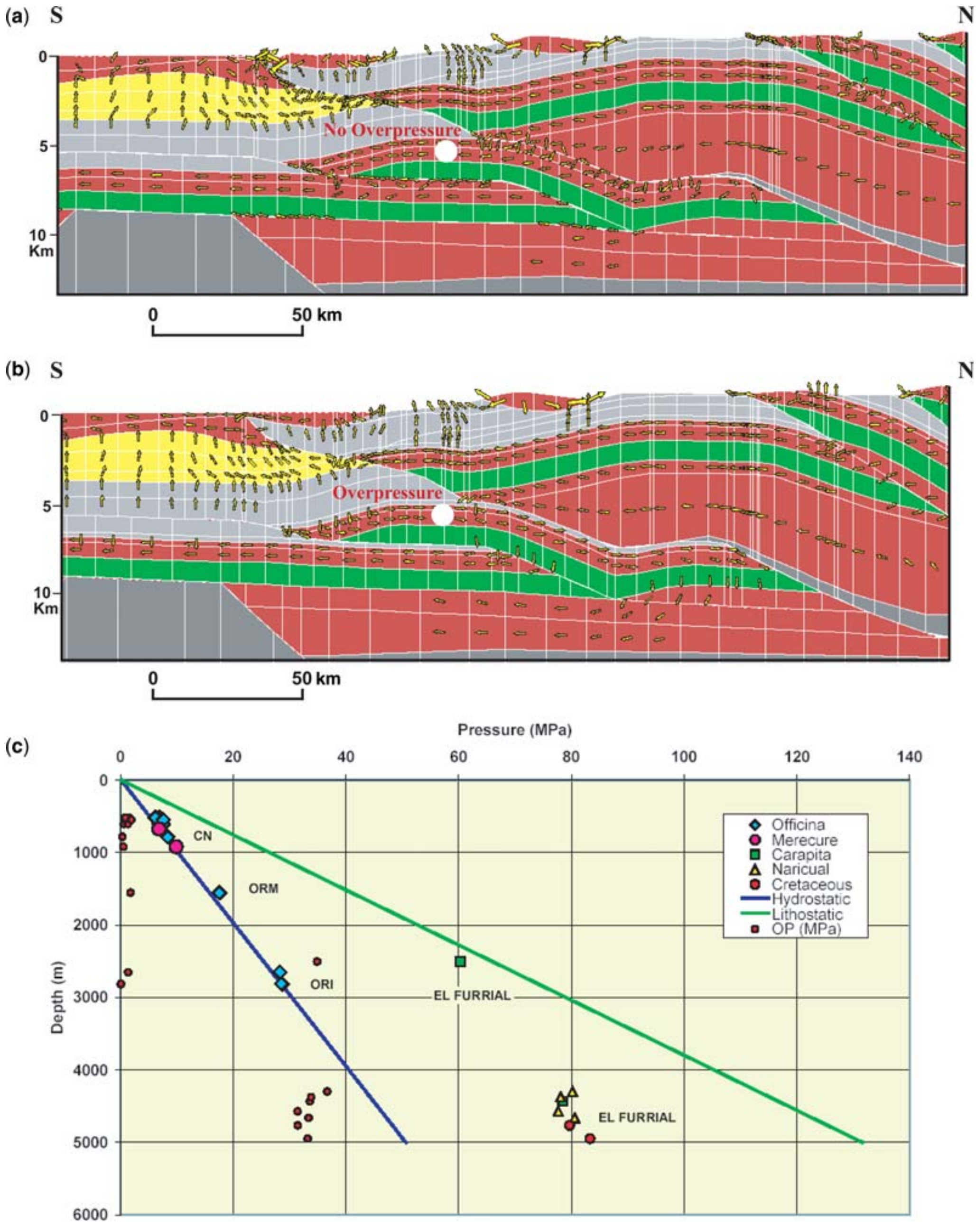

Fig. 2. 2D fluid flow and pore-fluid pressure modelling along the same Eastern Venezuelan transect. Green horizon = Querecual source rock; underlying red unit = Barranquin siliciclastic aquifer; overlying red unit = Naricual Oligocene reservoir. (**a**) Top section illustrates a geometric configuration which prevented the building of overpressures in the El Furrial reservoirs (white dot) because of the lack of permeability barriers between the hanging wall and the footwall of the Pirital thrust. (**b**) Bottom section outlines the real configuration of the thrust pile, with an intervening seal made up of Carapita shale between the Barranquin units of the hanging wall and the Naricual of the footwall of the Pirital thrust, this later configuration allowing the building of overpressures in the El Furrial trend. (**c**) Depth v. pore-fluid pressure plot from wells of the El Furrial trend.

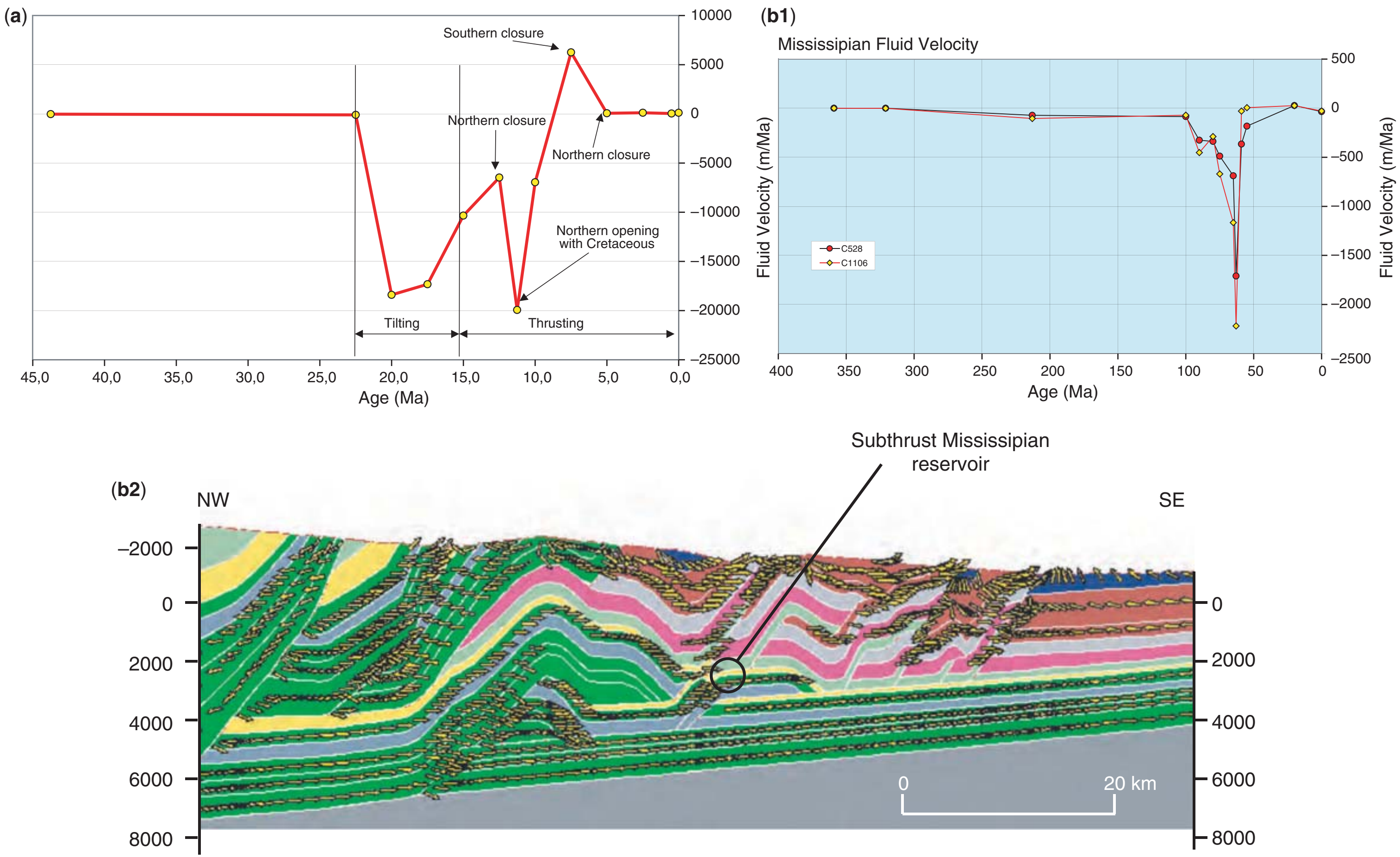

Fig. 3. Evolution of fluid flow velocity v. time within Oligocene sandstone reservoirs of the Eastern Venezuela transect (active orogen, **a**), compared to fluid flow velocity v. time in Mississippian carbonate reservoirs in the Canadian Rockies (fossil orogen, Banff–Calgary transect, **b**1). (**b**2) documents the current architecture and fluid flow pattern along the Banff–Calgary transect (the circle indicates the location of sub-thrust Mississippian reservoirs targeted in the fluid velocity modelling of 3**b**1).

2000). Generally first host-rock buffered fluids are squeezed out, then chemical compaction forms LPS stylolites. Later non-equilibrium fluids circulate through reopened structures. Palaeo-stress evolution reveals that the motor must be hydrofracturing. This deformation progrades through the foreland as a caterpillar-movement (Ferket *et al.* 2004).

Unlike offshore accretionary wedges, FTB are not only characterized by fluid flow controlled by lateral permeability barriers but also by the topography-driven, gavitational flow of meteoric water, which operates from the positive relief of the hinterland towards the adjacent low lands and is mostly confined to the shallow horizons of the foreland, that is above the compaction-induced permeability barrier that has been previously described.

The main differences observed in the results of Ceres modelling applied in Venezuela (a still currently active orogen), and the Canadian Rockies (where Laramide-related tectonic compaction stopped at the end of the Eocene, about 60 Ma) relate to the timing of squeegee fluid escape, which is Miocene in Venezuela (Fig. 3a), against Late Cretaceous in Canada (Fig. 3b1). Both systems are still affected by a gravitationally-driven, shallower flow of meteoric water, restricted to the Miocene flexural sequence in Venezuela and to the Cretaceous flexural sequence in Canada; that is, much shallower than the Oligocene sandstone reservoirs of El Furrial and the Mississippian carbonate reservoirs of the Rockies (Fig. 3b2).

Although it would not affect the results of these Venezuelan and Canadian models, it is important to notice that sea-level changes and palaeo-bathymetry are also important in controlling the development of overpressures in some foreland basins and adjacent foothills, as described in Albania by Vilasi *et al.* (2009).

Meteoric v. basinal signature of circulating fluids

Although large geochemical databases are now available to document the current distribution of meteoric v. saline waters in FTB, that is in the Canadian Rockies and in Taiwan, it is not always easy to characterize the origin of palaeo-fluids when fluid inclusions in diagenetic cements constitute the unique direct record left from these palaeo-circulations.

For instance, early studies made on fluid inclusions from cemented hydraulic fractures along the sole thrust of the Sicilian allochthon evidenced low salinities for the palaeo-fluids, these low salinity values being then interpreted as evidence for a meteoric signature (Guilhaumou *et al.* 1994; Larroque *et al.* 1996). Further $\delta^{18}O$ studies made by De Wever (2008) argue against this hypothesis, corroborated by other geochemical controls that rather suggest the smectite–illite transformation in Late Cretaceous to Palaeogene shale layers to be the main process accounting for the expulsion of such low salinity water. Similar processes have also been described for modern accretionary wedges (Vrolijk 1987).

The same debate also occurred for the nature of the palaeo-fluids (either meteoric or basinal) accounting for quartz-cementation in the El Furrial Oligocene reservoir in Eastern Venezuela. Because no formation water was yet available from the numerous wells located in the El Furrial trend, basically because they did not reach the oil–water contact, an attempt was made to derive palaeo-salinities of the formation waters by measuring Tm (melting temperature of the last ice crystal) in fluid inclusions (Bordas 1999; Roure *et al.* 2003). However, it turned out that the fluid inclusions were too small (less than 3 μm), thus precluding any accurate measurements of Tm. Further $\delta^{18}O$ studies made on the same cements ultimately evidenced the basinal, not meteoric signature of the palaeo-fluids, implying that the gravity-driven flow of meteoric water never went deeper than the regional lower Miocene, intra-Carapita seals (Schneider 2003).

Allochthon/foreland mechanical coupling, and further incidence of layer parallel shortening on reservoir damaging and pore-fluid pressure cyclicity

In many FTB, LPS imprint has been mapped using the magnetic susceptibility anisotropy (AMS). AMS studies have been proven successful in deciphering the strain acquisition mechanisms for both sandstone (e.g. Saint-Bezar *et al.* 2002) and limestone (e.g. Evans *et al.* 2003), allowing the description of a general AMS fabric acquisition path related to strain. During the pre-folding LPS, AMS fabric evolves from a sedimentary fabric to intermediate and tectonic fabrics (Averbuch *et al.* 1992; Aubourg *et al.* 1997; Aubourg 1999; Evans *et al.* 2003). Both in extensional (e.g. Mattei *et al.* 1997) and compressional strain regimes (e.g. Frizon de Lamotte *et al.* 1997, 2002), most of the studies emphasized that the magnetic fabrics are generally acquired in response to pre-folding deformation. As an example, the AMS fabric recorded in the FTB of the Rocky Mountain along the Flathead Valley–Waterton dam transect (Fermor & Moffat 1992), shows this very classic pattern of fabric evolution in the sandstone reservoir levels, from the sedimentary magnetic fabric in the undeformed foreland basin to

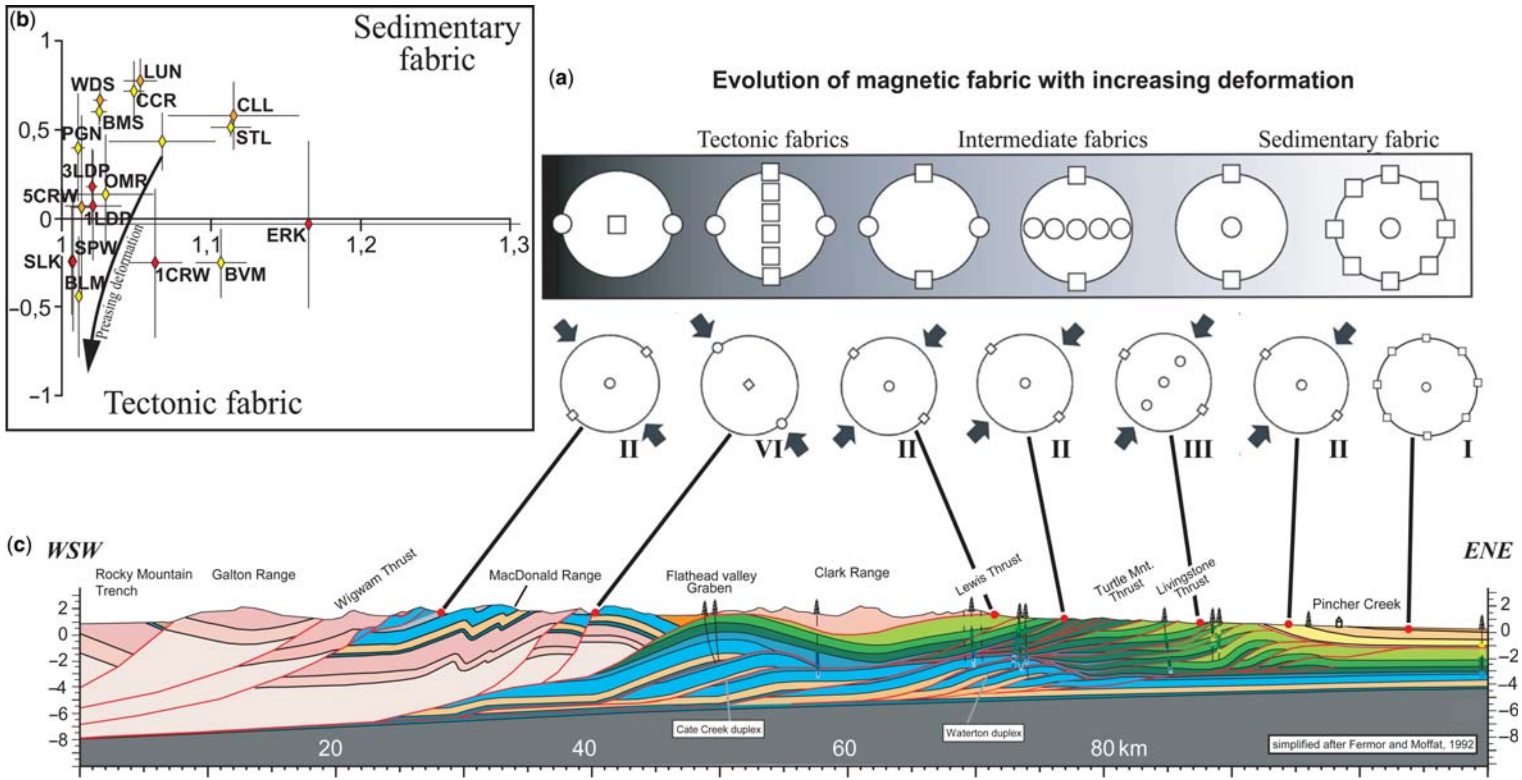

Fig. 4. Lateral evolution of AMS fabric along the Rocky Mountains transect (Fermor & Moffat 1992). (**a**) Classic pattern of evolution of magnetic fabric with increasing deformation (Averbuch *et al.* 1992); (**b**) Evolution of the magnetic ellipsoid shape across the belt; (**c**) Evolution of the magnetic fabric from the foreland to the Main Range.

more evolved intermediate and even tectonic fabric within the belt (Fig. 4).

The same pattern of magnetic fabric evolution has also been documented in Eastern Venezuela (Roure *et al.* 2003), where integration of various datasets ranging from seismic profiles to thin sections, analytical work and modelling also allowed for the appraisal of the quality of sub-thrust Oligocene sandstone reservoirs of the El Furrial trend. Their porosity–permeability evolution results from mechanical and chemical compaction, both processes interacting in response to sedimentary burial, horizontal tectonic stress and temperature.

Actually, the main episode of sandstone reservoirs deterioration occurred in the footwall of frontal thrusts at the time of their nucleation, when the evolving thrust belt and its foreland were mechanically strongly coupled (Fig. 5). The related build-up of horizontal tectonic stresses in the foreland induced LPS at reservoir scales, involving pressure-solution at detrital grain contacts, causing *in situ* mobilization of silica, rapid reservoir cementation by quartz-overgrowth and coeval porosity and permeability reductions (Roure *et al.* 2003, 2005*b*).

The age and duration of such quartz-cementation episodes can be roughly determined by combining micro-thermometric fluid inclusion studies with 1D and 2D basin modelling. In the case of the Oligocene El Furrial sandstone of Eastern Venezuela, homogenization temperatures (Th) in quartz-overgrowth cements reflect a very narrow temperature range (110–130 °C), whereas the current reservoir temperature exceeds 160 °C. When plotted on burial/temperature v. time curves derived from 1D or 2D basin models calibrated against bottom hole temperatures (BHT) and maturity rank of the organic matter, it becomes obvious that cementation occurred during a very narrow time interval, no longer than a few million years, when the reservoir was not yet incorporated into the orogenic wedge (Fig. 5; Roure *et al.* 2003, 2005*b*).

Such techniques of combined micro-thermometry and basin modelling can also be used for dating any other diagenetic episodes, provided the reservoir was in thermal equilibrium with the overburden at the time of cementation (without advection of hot fluids). Moreover, forward diagenetic modelling at reservoir scales can benefit from output data from basin modelling such as reservoir temperature, length of the diagenetic episode and, in the case of diagenesis in an open system, fluid composition and velocities. For the quantification of fluid–rock interactions in the pore space of a reservoir or along open fractures transecting it, information on these parameters is indeed required. Furthermore, the composition of the fluids involved and the kinetic parameters, which control the growth or dissolution of various minerals present in the system, must be known.

Error bars in palaeo-burial reconstructions related to lateral and temporal variations in the heat flow

How to account for high maturities in the Serraña (Eastern Venezuelan transect)?

Earlier in the paper we described the overall results of the integrated workflow applied for fluid flow modelling and HC appraisal only for the southern part of the Eastern Venezuelan transect. In fact, other complications occur further to the north along this transect. The main problem is to account for the very high maturity ranks measured for the Cretaceous Querecual source rocks in the Serraña del Interior, north of the Pirital thrust and its Morichito piggyback basin, where basically all the Cenozoic series have been removed by erosion (Fig. 1).

As mentioned in the introduction, if they are constrained only by maturity ranks of the organic matter (Tmax and Ro), basin modelling tools cannot solve directly the two unknowns of this geological problem, that is, the maximum palaeo-temperature and palaeo-burial reached by the Querecual source rocks.

Indeed, two extreme hypotheses can be proposed to achieve the same results and match observed maturities:

Hypothesis 1 would consider that the Serraña was located at the place of an early Miocene foredeep basin, which became subsequently eroded, the observed maturities entirely resulting from the early Miocene burial of the Cretaceous source rocks beneath the foreland deposits, thus predating their tectonic accretion within the thrust wedge;

Hypothesis 2 would instead consider that the Serraña was located in the distal part of the former passive margin, not far from the ocean–continent transition, thus implying a higher heat flow regime than in the adjacent foreland domain which developed on top of the thermally equilibrated cratonic lithosphere, and a shallower sedimentary burial before tectonic accretion.

In fact, both mechanisms are likely to contribute to part of the observed maturities, and in the lack of other controls (such as palaeo-barometers or age constraints), several solutions can be proposed by the model to match the data, mixing to various degrees the unknown thickness of the early Miocene series prior to their erosion, compensated by a given heat flow during the early, pre-orogenic stages of the transect evolution.

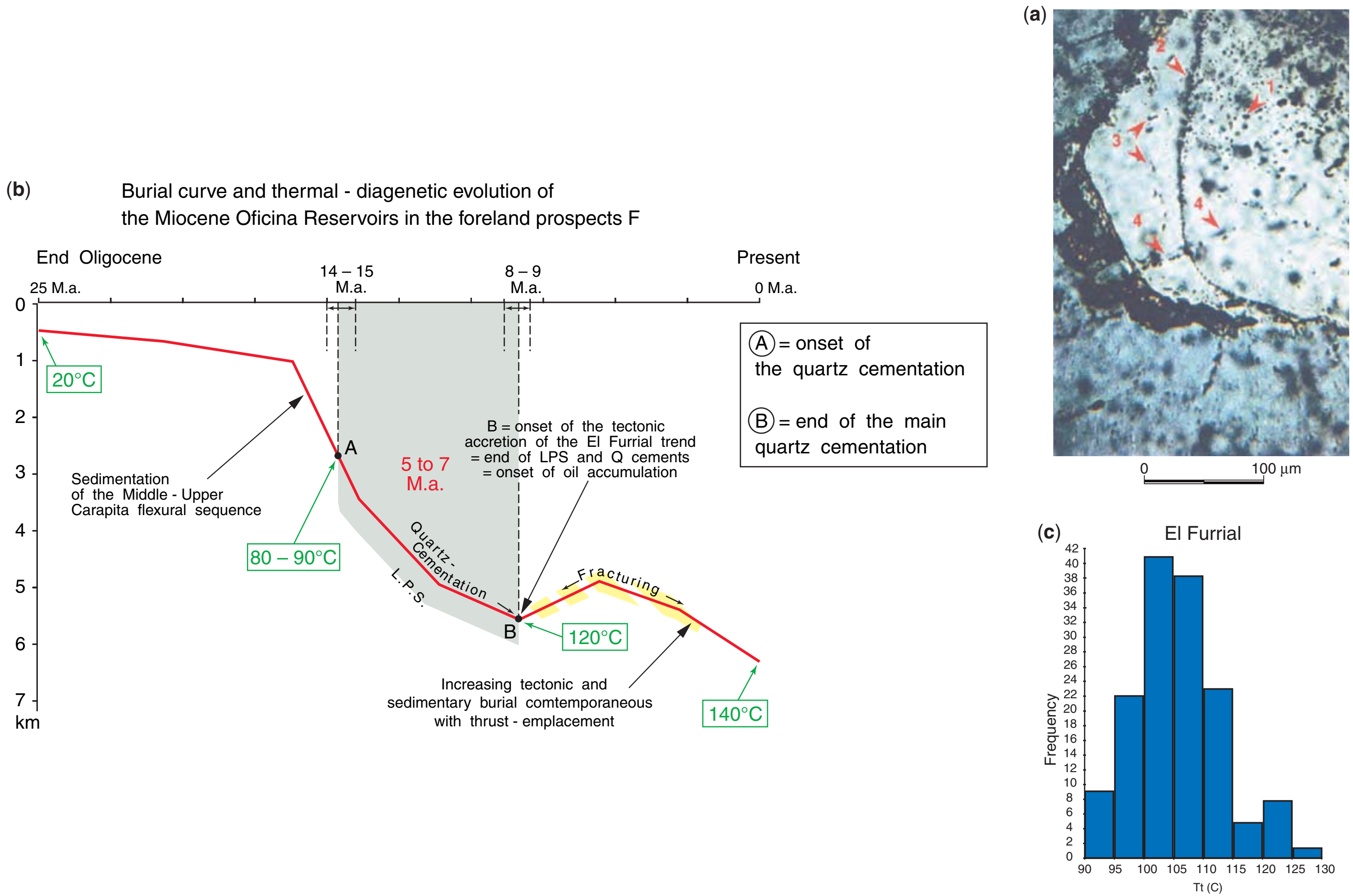

Fig. 5. (**a**) Quartz-overgrowth in the Oligocene Naricual reservoir of El Furrial; (**b**) Burial/temperature v. time curve of the Oligocene Naricual reservoir of the El Furrial trend; (**c**) Histogram of Th measured in the fluid inclusions of quartz-overgrowth of the same Naricual reservoir (modified from Roure *et al.* 2003, 2005*b*).

Roll-back of subduction, slap detachment and corner flow of the mantle in the hinterland: their incidence on lateral and temporal changes in the thermicity of FTB

Similar spatial and temporal changes in the basal heat flow have been documented in the Southern Apennines, where the various Cretaceous platform units involved in the Plio-Quaternary deformations were all derived from the former passive margin of Apulia (Casero *et al.* 1991; Mosca *et al.* 2004; Sciamanna *et al.* 2004). As such, the Apulian Platform in the foreland and sub-thrust units, and the Apenninic Platform units at the top of the allochthon, were both affected by the same basal heat flow during the Palaeogene and Miocene. However, they are currently located in two very distinct geodynamic environments, that is the cold thermal regime associated with the foredeep and outer portion of the thrust belt in the east (both developed on top of the thick, thermally equilibrated Apulian lithosphere), and the hot peri-Tyrrhenian province, where the lithosphere has been strongly attenuated during the Plio-Quaternary opening of the Tyrrhenian Sea (Fig. 6).

As in the Southern Apennines, hot thermal regimes can develop in the hinterland of fold and thrust belts during or after the late stages of compression and foothills emplacement, in association with an asthenospheric rise.

Roll-back of the subduction and slab detachment have thus been advocated as the two main processes accounting for back-arc extension, resulting in the lateral changes of lithosphere thickness and basal heat flow observed beneath the hinterland of the Carpathians (Pannonian Basin) and the Maghrebides–Apennines system as a whole (Algerian/Provençal and Tyrrhenian basins), respectively.

Corner flow of the asthenosphere induced by the subduction of the Pacific is advocated as the main mechanism for post-Laramide development of metamorphic core complexes, crustal extension and anomalous topography in the North American Cordilleran domain (Fig. 7; Basin and Range, Canadian Rockies, Mexican Sierras; Vanderhaeghe *et al.* 2003; Teyssier *et al.* 2005; Hardebol *et al.* 2007, 2009), as well as in the Altiplano in South America.

Timing of unroofing and hydrocarbon prediction beneath crystalline basement and ophiolitic units (input of AFT)

Uncertainties in thermal modelling can be drastically reduced when the timing of unroofing of the allochthon can be reasonably constrained by low thermal geochronology (e.g. apatite fission tracks, AFT), as discussed below with two new case studies. AFT data provide absolute age–temperature paths, which can be in turn converted to palaeo-depths if assuming a palaeo-heat-flow. Conversely, they can also provide constrains on the palaeo-heat-flow when independent depth estimates can be made.

Impact of the crystalline basement of the Garzon Massif on the thermicity of footwall strata

In the Middle Magdalena Basin in Colombia, the Cretaceous source rocks of the La Luna Formation have been locally overthrusted by the crystalline basement of the Garzon Massif, which constitutes the southernmost extent of the Eastern Cordillera (Fig. 8). Although the Garzon Massif is currently bald of Neogene sediments, it was part of the initial Late Cretaceous to early Miocene foredeep basin that extended east of the Central Cordillera, prior to the development of late Miocene to Plio-Quaternary foreland basement uplifts and basin inversions which characterize the northwestern part of the South American craton (i.e. Merida Andes and Sierra de Perija in Western Venezuela and Eastern Cordillera in Colombia).

Serial structural transects have been compiled from surface and subsurface data across the Magdalena Basin and adjacent Garzon Massif, and subsequently modelled with Thrustpack (coupled 2D kinematic and thermal modelling) in an attempt to check the 3D distribution of oil kitchens and drainage areas. Although well data allowed calibration of the heat flow in the Magdalena Basin itself, where no major erosion occurred, AFT data obtained by van der Wiel and Andriessen (van der Wiel 1991; van der Wiel & Andriessen 1991) from surface samples of the Garzon Massif were very critical to actually constrain the timing of the exhumation of this unit above the partial annealing zone (i.e. when the current topographic surface of the crystalline allochthon crossed the 110 °C isotherm). According to AFT, the Garzon Massif has been uplifted and eroded since about 6 million years ago, with a cumulative erosion of Mesozoic to Miocene series amounting to about 6 km.

Results of thermal modelling are shown in both maps and sections, in order to better understand the incidence of lateral and vertical heterogeneities in the conductive properties of the rocks (Fig. 8). Surprisingly enough, there is a delay in the maturation of Cretaceous source rocks beneath the Garzon Massif compared to adjacent horsts. The high conductivities in the basement helped to (1) mature the source rocks faster above the palaeo-horsts than in adjacent grabens, and (2) drive the heat quickly toward the surface across the basement allochthon, thus keeping the maturity rank of underlying

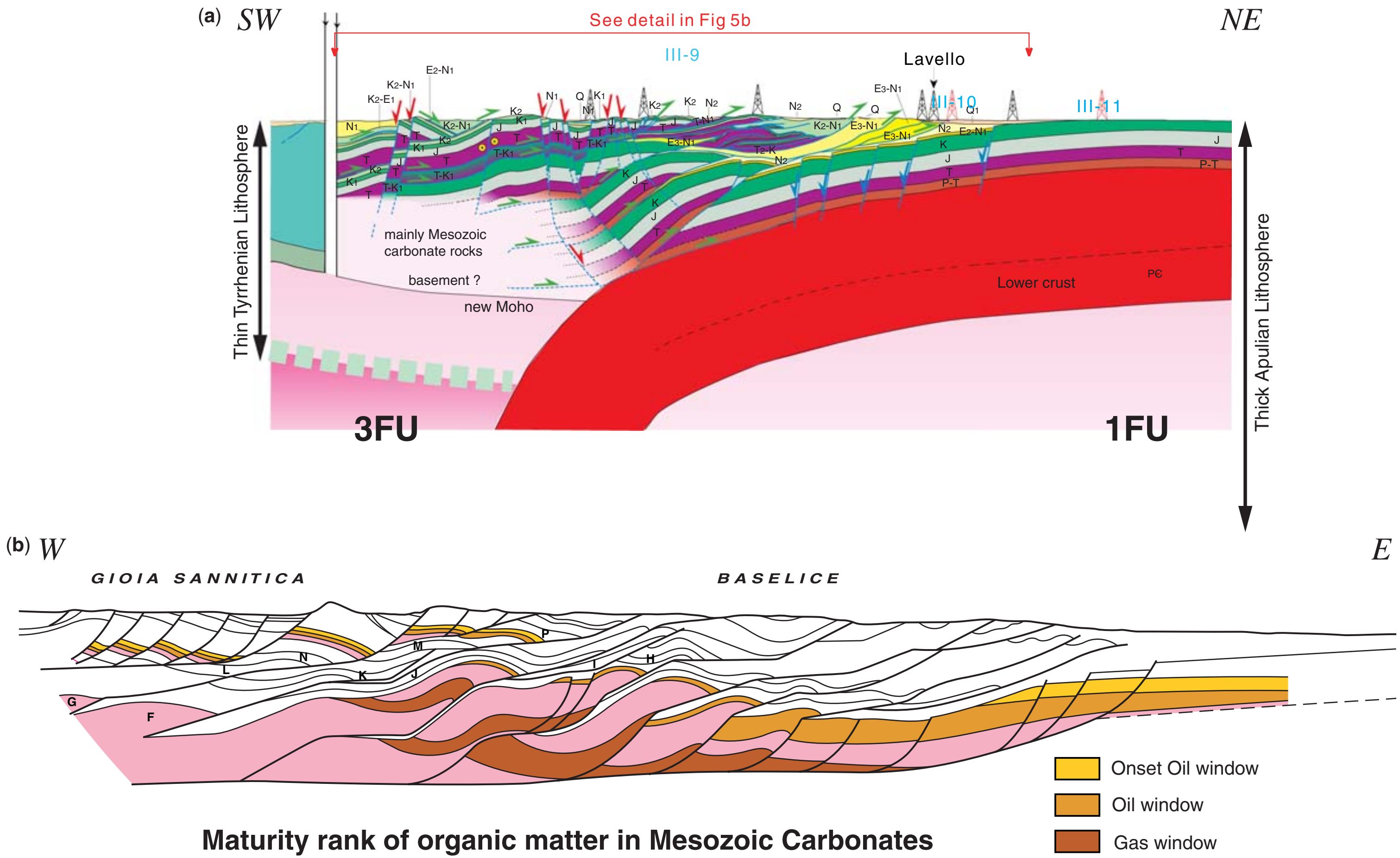

Fig. 6. (**a**) Structural and lithospheric-scale sections of the Southern Apennines (modified after Carminati *et al.* 2004), outlining the current crustal and lithosphere thickness, and lateral variations observed in the heat flow (changing from one HFU (Heat Flow Unit) in the Adriatic foreland with thick lithosphere, to up to three HFU in the Tyrrhenian side of the section, where thin lithosphere occurs). (**b**) Result of 2D thermal modelling along the same transect, outlining the current maturity ranks of the organic matter in Mesozoic platform carbonate units for both the underthrust Apulian Platform (lowermost unit of the tectonic pile) and the far-travelled Apenninic Platform (uppermost unit of the tectonic pile).

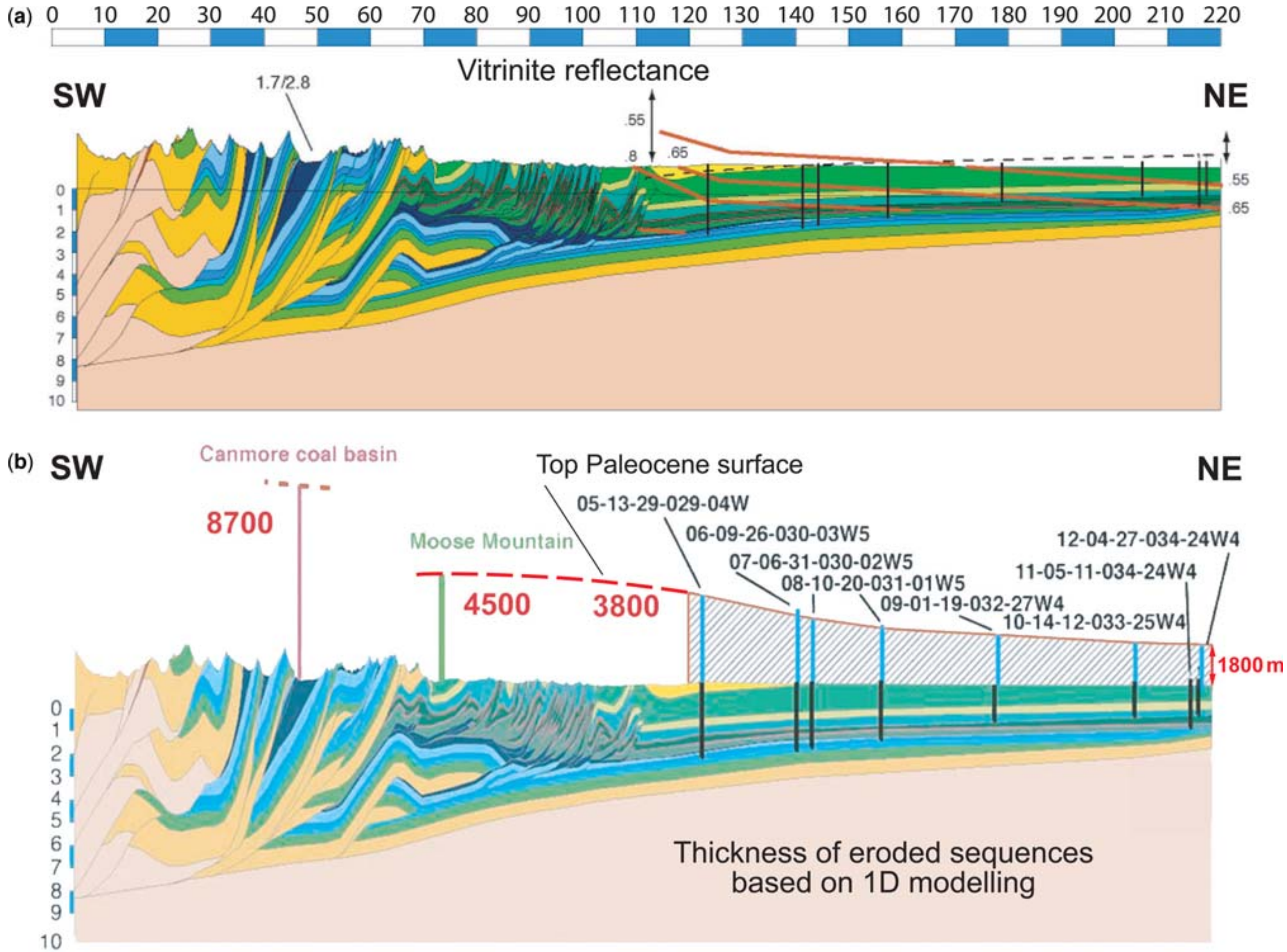

Fig. 7. Erosional profile along the Banff–Calgary transect, recording the effect of post-Laramide asthenospheric rise and related thermal doming and unroofing of the former orogen. (**a**) present distribution of vitrinite reflectance (Ro) data; (**b**) thickness of eroded sediments derived from 1D modelling of selected wells.

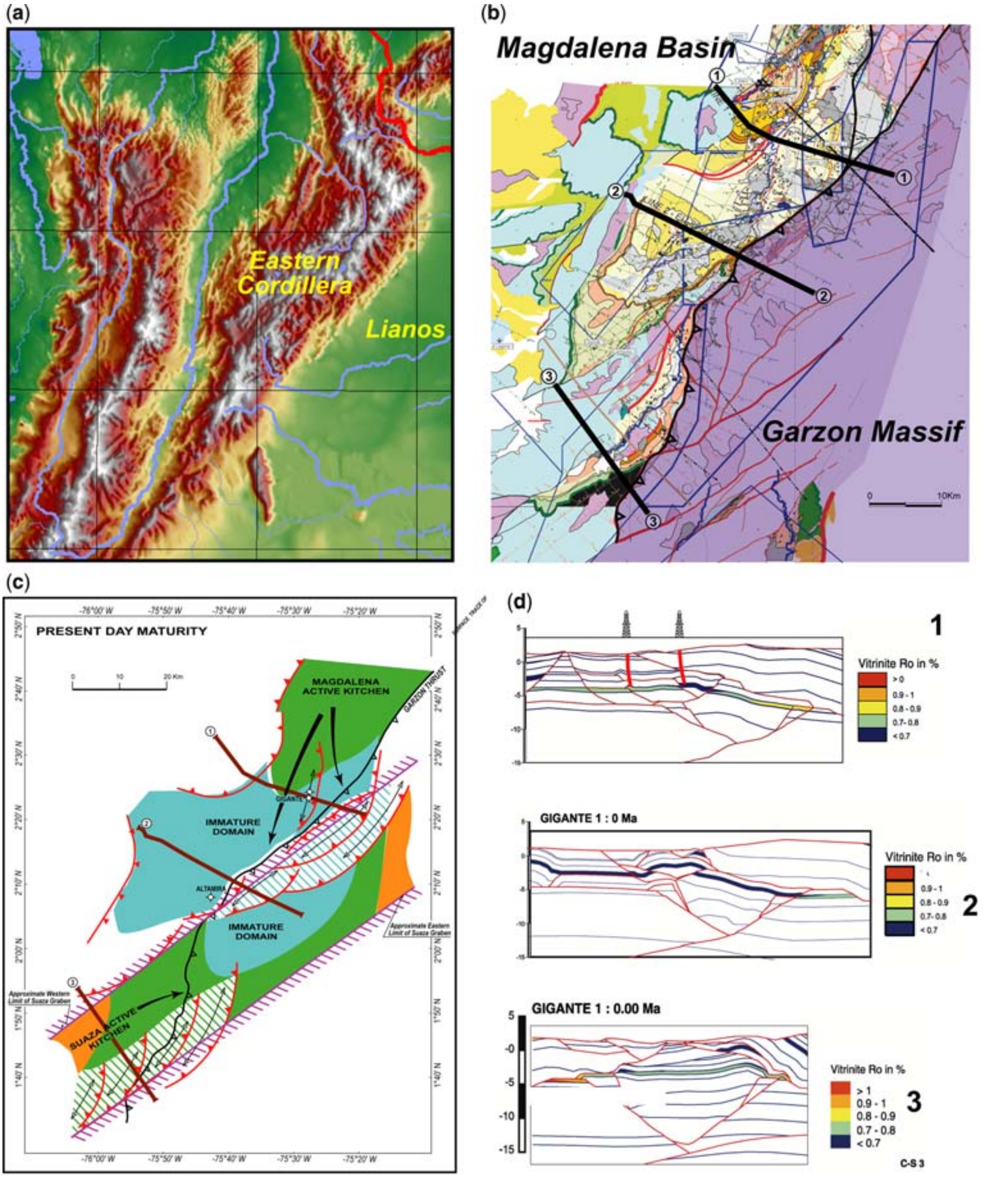

Fig. 8. Serial 2D result sections and maps derived from forward kinematic and petroleum modelling in the Middle Magdalena basin, outlining the effects of high conductivities of the Garzon crystalline allochthon on the maturity pattern of underthrust series (after Roure *et al.* 2005*a*).

sediments. This maturity rank indeed displays lower values beneath the Garzon Massif.

Impact of the Mirdita Ophiolite on the thermicity of footwall strata

Well-known petroleum provinces extend in the foothills of the Outer Albanides and in the Arabian foreland of the Oman Range, two orogens which are famous by the widely exposed ophiolitic units of their hinterlands, that is the Mirdita Ophiolite in Albania, and the Semail Ophiolite in the United Arab Emirates and Oman, respectively. However, companies have been reluctant until now to explore close or even beneath these palaeo-oceanic units, because of the uncertainties on the maturity ranks reached by the organic matter in the footwall units. For instance, most ophiolitic belts are underlain by a metamorphic sole made up of high pressure blueschists, amphibolite or greenschists, the age of this metamorphism being commonly much older than the last episodes of thrusting.

Unexpectedly, and despite being dominantly made up of peridotite and gabbros, ophiolites can provide good lithotypes for AFT dating when they host oceanic plagiogranites, whose study provides a direct control on the timing of exhumation.

In Albania, HC exploration is currently focused on oil-bearing Late Cretaceous to Paleocene carbonate turbidites of the Ionian Basin near the Vlora–Elbasan lineament, as well as on biogenic gas and thermogenic condensates hosted in Neogene sandstone reservoirs of the Peri-Adriatic Depression (Fig. 9). Alternatively, seismic imagery has also identified deep Mesozoic plays in sub-thrust duplexes involving the Mesozoic platform-to-basin transition, beneath the shallower Cretaceous platform allochthon of the Kruja thrust sheet, just west of the Mirdita Ophiolite. Furthermore, oil seeps are common in the Kruja Zone, and Thrustpack and Ceres modelling still predict the occurrence of active oil and gas generation along the eastern border of the Peri-Adriatic Depression and Ionian Basin, at the boundary between the Outer and Inner Albanides (Vilasi *et al.* 2009).

The main challenge for the exploration in Albania remains to predict the real HC potential of sub-thrust platform and basinal units which are currently still stacked in the hinterland, east of the Kruja Zone, beneath the ophiolite, which constitutes the topmost unit of the tectonic pile.

The work done recently by Muceku *et al.* (2007) in Albania demonstrates that the Mirdita Ophiolite, which was first obducted during the Mesozoic (post-obduction Cretaceous piggyback basin), was already deeply eroded at the time of its final thrusting on top of the Outer Albanides during the Neogene. Thus, the Mirdita Ophiolite unit had only a very limited impact on the burial and thermal evolution of underlying source rocks. The AFT ages obtained by Muceku *et al.* have been plotted on a regional structural transect across the Albanides (Fig. 9). The AFT data provide a Palaeogene age for the unroofing, demonstrating that the Mirdita unit was already at temperatures lower than 110 °C in late Oligocene and early Miocene times, when the Mesozoic and Palaeogene units of the Ionian Basin and Peri-Adriatic Depression became underthrust beneath the allochthon. These data would also provide an invaluable control when modelling further the maximum palaeo-burial and palaeo-temperatures reached by the lower plate at the time of the Mirdita emplacement over the Outer Albanides.

Seemingly, the young AFT ages evidenced by Muceku east of the Mirdita Ophiolite, in the vicinity of a tectonic window already described by Collaku *et al.* (1990), provide another direct chronological control on the timing of underplating or out-of-sequence duplexing in the lower plate. This AFT age indeed records the time when the sole thrust of the allochthon was refolded by the development of sub-thrust anticlines in the lower plate, the latter being coeval with the age of the deformation front in the foothills.

As already evidenced for the maturity ranks of the Cretaceous source rocks beneath the Garzon Massif in Colombia it is not unlikely that high thermal conductivities in fractured peridotites and volcanic rocks could have induced a rapid heat transport toward the surface, thus resulting in a delay in the maturation of underlying units, an effect similar to the heat pumping of salt diapirs, which is discussed below.

Incidence of salt redistribution on further hydrocarbon prediction

Recent oil discoveries have been made in the deep offshore of passive margins in the US part of the Gulf of Mexico and West Atlantic margin in Brazil, beneath thick salt accumulations. Surprisingly enough, hydrocarbon fluids are still present in these ultra-deep reservoirs located in the distal portions of passive margins, close to the continent–ocean transition. As evidenced in the Colombian study, high conductivities of the salt bodies are likely to efficiently drive out the heat to the surface, and to induce a relative delay of source rock maturation beneath the salt, compared to what would be expected beneath a similar thickness of less conductive siliciclastics blanketing the sediments below (O'Brien & Lerche 1987).

As in passive margins, the remobilization and spatial redistribution of salt in fold and thrust belts make it challenging to calibrate the thermal models, because of the strong discrepancy observed between (1) maturity records of the organic matter measured in the wells, which were eventually achieved before the regional redistribution of the salt, and (2) the current distribution of BHT and geotherms, which accounts for the present salt distribution. The same problem actually impacts geothermal gradients measured at the crest of salt diapirs, as they cannot be extrapolated laterally to adjacent synclines, the latter being most likely devoid of salt. In FTB a good example of such salt-related problem is provided by the Salt Range and Potwar Basin in Pakistan, where the Infra-Cambrian Salt has been greatly redistributed during the Miocene. The salt series probably was relatively isopachous at the time of deposition, and remained undeformed until the end of the deposition of the passive margin sequences, from the lower Palaeozoic to the Eocene, all these

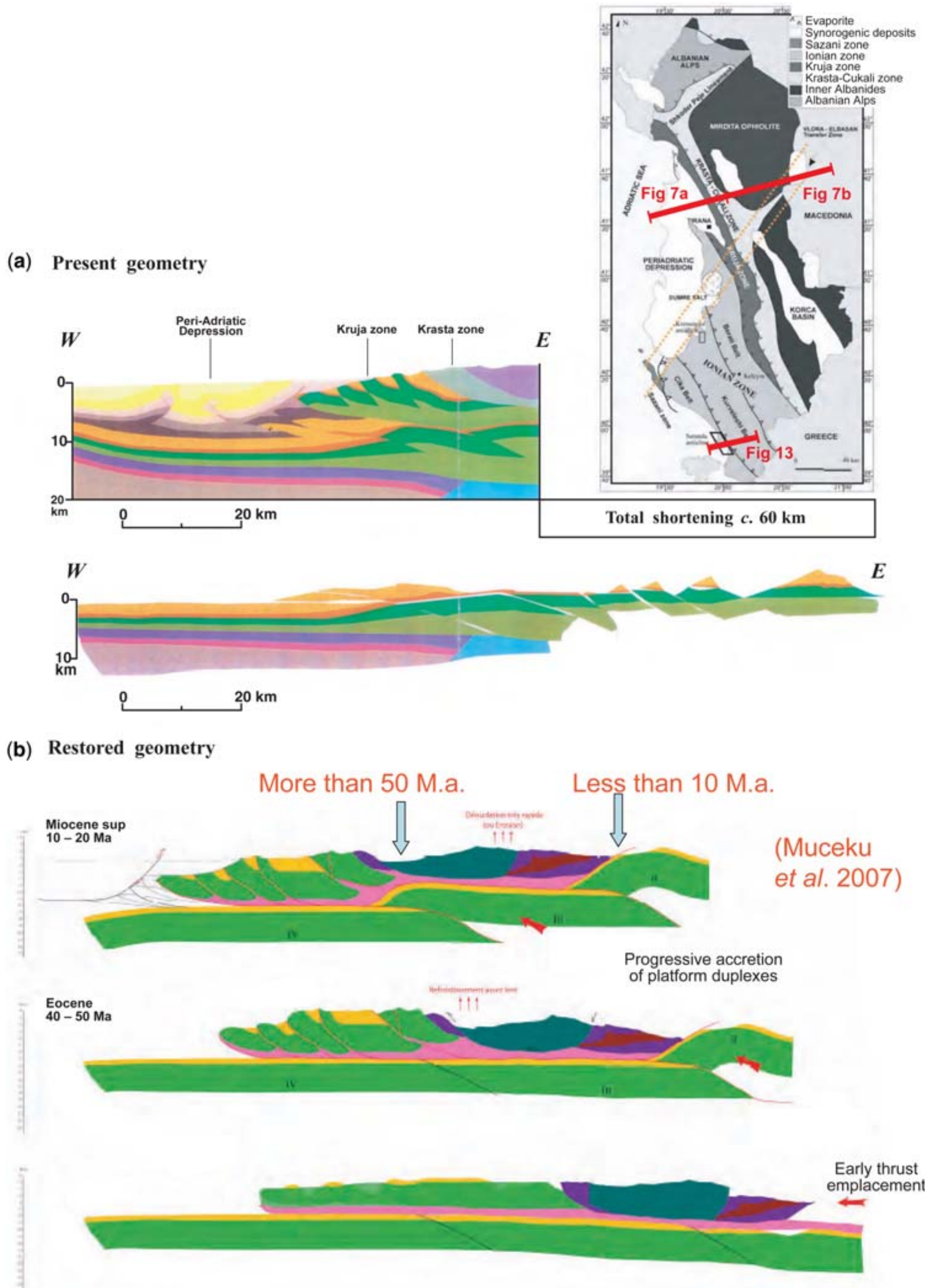

Fig. 9. Structural section across the Inner Albanides, with plot of AFT data obtained by B. Muceku *et al.* (2007). Location map (after Albpetrol 1995). (**a**) Structural and restored section across the Peri-Adriatic Depression and Kruja foothills, west of the Mirdita Ophiolite, based on seismic interpretation and Locace restoration. Notice the lateral thinning of Mesozoic carbonates from the Kruja Platform in the east towards the Ionian Basin to the west. (**b**) Eastern continuation of the same transect across the Mirdita Ophiolite, and current distribution of AFT data. Notice that tectonic duplexing in the lower plate post-dates the thrust emplacement of the Kruja units and main erosion phase of the ophiolite.

layers being isopachous in seismic profiles, with no record of syndepositional halokinesis.

The first compressional episode was synchronous with the deposition of the Neogene Siwalik molasse, resulting in thin-skinned tectonics. This early deformation episode accounts for the thrust emplacement of the Salt Range at the southernmost limit of the former salt basin during the late Miocene, with up to 20 km of southward displacement of the allochthon, and for the local development of salt pillows within the Potwar Basin further north (Fig. 10). The structural style associated with the Plio-Quaternary deformation was instead dominantly thick-skinned, with the development of pop-up structures and fish tails in the sedimentary cover, accommodating the local transpressional inversion of underlying infra-salt normal faults and grabens (Fig. 10; Roure 2008).

This tectonic agenda is consistent with the maturity rank (Tmax) of the organic matter in the infra-Cambrian series of the Salt Range, which are indeed still immature because this frontal structure behaved as a growth structure during the late Miocene. Early tectonic accretion and uplift prevented this part of the basin becoming deeply buried beneath the Siwalik series. It agrees also with the magneto-stratigraphic dating of growth strata around the surface anticlines of the Potwar Basin, which are Pliocene–Quaternary in age (Burbank & Johnson 1982; Burbank 1983; Burbank & Beck 1989), thus younger than the *c.* 10 Ma old emplacement of the Salt Range (Zeilinger *et al.* 2007).

Both 1D (Genex) and 2D (Thrustpack) thermal modelling have been performed on various regional transects crossing both the Potwar Basin and the Salt Range, dominantly oil, province. Although infra-Cambrian source rocks amounting up to 20% of TOC (Total Organic Carbon) occur in the Salt Range, where they are still immature, oil-source rocks correlations demonstrate that most if not all of the oils discovered in the Potwar Basin derive from younger Palaeogene sources associated with the Paleocene Patala Shale and possibly also locally with Eocene carbonates.

The timing of petroleum generation can easily be derived from geological observations. Because the Patala shale is still immature or at the onset of the oil window in the cored Pliocene–Quaternary anticlines, oil generation is assumed to have occurred in adjacent synclines, which recorded increasing burial during the growth of the anticlines, oil migration and trapping being obviously post-Miocene.

This latter knowledge is important when addressing the thermal modelling, because all the BHT data come from anomalous points (anticlines), where the presently high geothermal gradient only relates to the recent thickening of the salt layer in the core of Pliocene–Quaternary anticlines. If misused by direct lateral extrapolation over the entire basin, these high heat flow values would result in the prediction of a late gas potential (Fig. 10; overmaturation of the Paleocene source rocks). Instead, calibration of fictive 1D wells or 2D Thrustpack modelling is more accurate when using solely the maturity ranks of the Patala Shale measured in the same wells, because it relates to frozen maturities achieved prior to the tectonic uplift, at a time the geothermal gradients were still low and equal over the entire basin (i.e. before the salt remobilization).

Use of hydrocarbon-bearing fluid inclusions in palaeo-burial reconstructions

Th (homogenization temperature) measurements in syngenetic fluid inclusions in minerals are mainly used in reservoir studies to estimate the minimal temperature of diagenetic fluids at the time of cementation of fractures in carbonate reservoirs and of development of quartz-overgrowth in sandstone reservoirs. Therefore this temperature should be corrected by a factor relative to the composition of the fluid and the pressure at time of fluid entrapment (Roedder 1984). This correction may be small and then is often neglected in basin modelling of petroleum occurrences because of low salinities aqueous systems (0–3 wt%) with high CH_4 in solution and relatively low pressure values (300 bars) attained in sedimentary basins. In foothills areas, using Th data only provides valuable information for calibrating petroleum modelling at different scales when pressure is high and tectonically dependent and basinal fluids are involved. However, the minimum palaeo-temperature reached by a given sample does not tell directly when this temperature was reached, nor at which palaeo-burial, making the pressure estimate and then the correction factor unknown, error bars in temperature being likely to exceed several tens of degrees Celsius.

Fortunately, in some cases it is possible to get accurate constraints for calibrating a basin model. Because of great immiscibility of oil and aqueous phases, aqueous inclusions can develop synchronously (i.e. at the same pressure and temperature) with hydrocarbon-bearing inclusions, within the same fluid inclusion generation in cements, thus providing a means for solving both the palaeo-temperature and palaeo-pressure of the fluids circulating in the studied reservoir at the time of cementation. The technique applied to derive temperature (T) and pressure (P) values from these two types of fluid inclusions in the same set relies on the different thermodynamic properties of the two fluids. PT isochoric modelling (PT evolution when keeping the volume unchanged) can be addressed, provided density and composition of aqueous and hydrocarbon

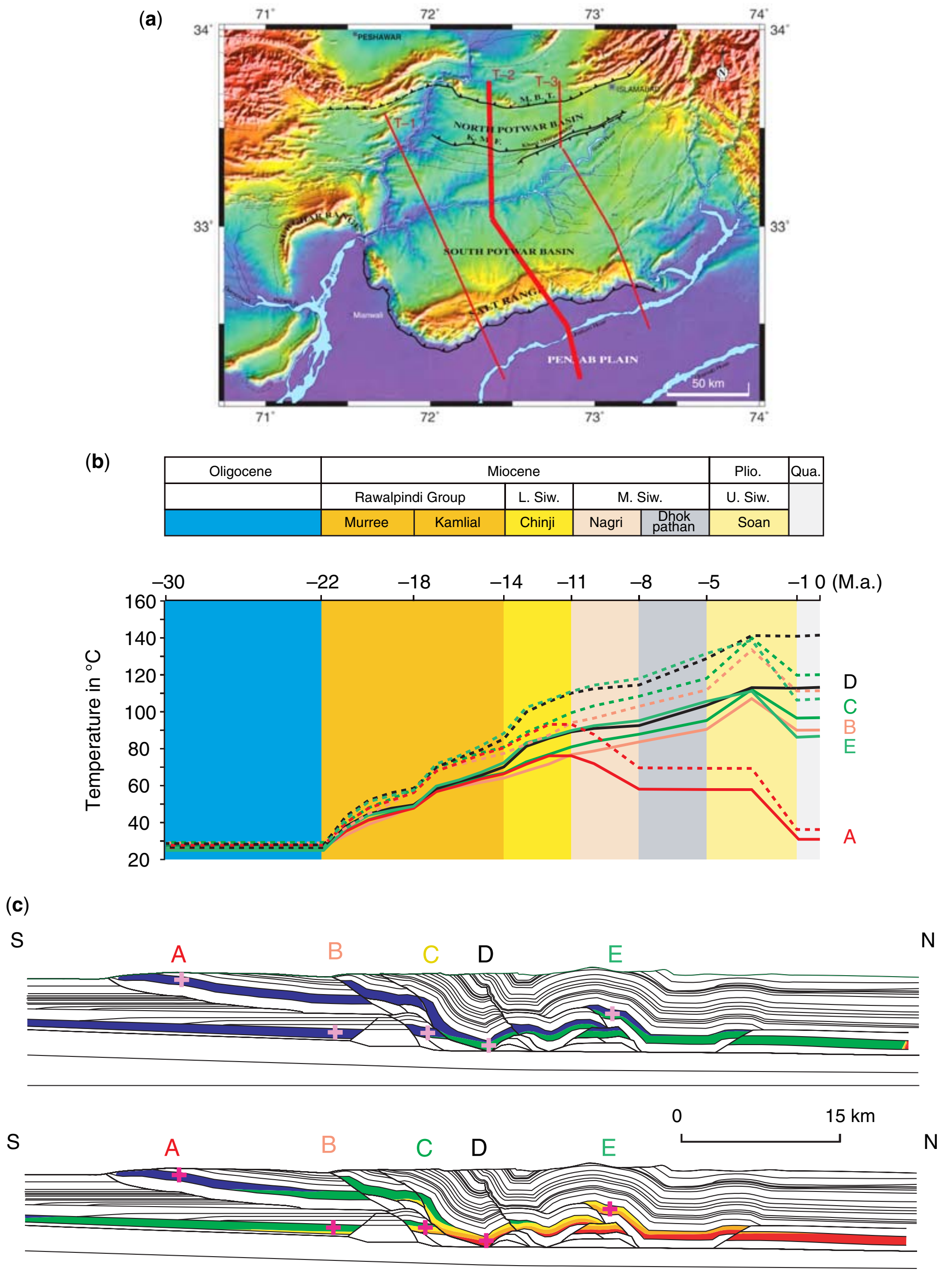

Fig. 10. 2D thermal modelling in the Salt Range–Potwar Basin, outlining the effect of lateral and vertical salt redistribution on temperature profile and overall maturity distribution in potential source rocks. (**a**) Location map; (**b**) Temperatures v. burial curves of the Eocene carbonate reservoir for the low heat flow hypothesis (full line) and high heat flow hypothesis (dashed line), respectively; (**c**) Top section (low heat flow hypothesis) matches the maturity rates of the organic matter; Bottom section (high heat flow hypothesis) was built to match present BHT in available wells. In the latter hypothesis, the resulting maturities are erroneous, because BHT are strongly influenced by salt pillows beneath the anticlines, and are not representative of the regional thermicity.

phases can be well defined individually by joint micro-thermometry and FTIR (Fourier Transform Infra-Red spectrometry) *in situ* analysis (Guilhaumou & Dumas 2005). For a specific composition and density, the intersection of the hydrocarbon isochore at the aqueous fluid homogenization temperature or in some case (low dissolved CH_4) with the aqueous isochore (Thiery *et al.* 2006), provides an accurate estimate of both pressure and temperature at the time of fluid inclusion trapping and then T and P values of the natural system at the time of crystallization/cementation (Guilhaumou *et al.* 2004; Ferket *et al.* 2010). Two applications of this integrated technique are described below.

Palaeo-burial reconstruction of hydrothermal karsts

Fluorite deposits occur in karstified platform carbonates of many FTB, for example in Baluchistan (Koh-i-Maran, in the Khirtar Range, Western Pakistan; Fig. 11a) and in Tunisia (Hamman Zriba, North–South Axis; Fig. 11b). Mesozoic carbonates hosting fluorite and MVT (Mississippi Valley Type) ore deposits are directly overlain by thick shale series. Early interpretations consider the latter as unconformable above a palaeo-emersion surface.

When studied in detail however (Guilhaumou *et al.* 2000, 2004; Benchilla *et al.* 2003), these two sequences do not show any evidence of emersion, thus precluding the former assumption that these karsts were meteoric in origin.

Integrated studies coupling petrography with the study of fluid inclusion and basin modelling have now demonstrated that both karst development and fluorite deposition occurred at the time these carbonates were deeply buried beneath the overlying seals, that is during a much younger episode of squeegee expulsion of basinal fluids at the onset of foothill development and regional tilting of the foreland basin, and not during an emersion event occurring during the passive margin stage.

As a matter of fact, these fluorite deposits are stratiform, and located at the top of porous carbonates which probably helped channelizing the basinal fluids when flushed updip the foreland flexure. Assuming that in both cases the circulating fluids were thermally equilibrated with the overburden (which would not be the case if fluorite occurred in vertical conduits such as faults and fractures), and that the pore-fluid pressure was close to hydrostatic (no evidence of hydraulic fractures), T and P values derived from the crossing of the two isochores of aqueous and oil-bearing fluid inclusions hosted in the fluorite of these ore deposits can be considered as representative of the palaeo-temperature and palaeo-burial of the host carbonate reservoirs at the time of the squeegee episode of fluid circulation.

The use of fluid inclusions for constraining the architecture of the Laramide flexure in Eastern Mexico

The Cretaceous platform carbonates of the Córdoba allochthon, in the southeasternmost part of the North American Cordillera in Mexico, are almost bald of any synflexural nor synorogenic sediments. Only limited outcrops document the gradual changes from shallow water Cenomanian carbonates towards deepwater Late Cretaceous–Paleocene turbidites. The initial thickness of these flysch deposits is unknown. Furthermore, seismic data document a presently east-dipping attitude of the crystalline basement beneath these allochthonous Mesozoic carbonates (Fig. 12a). The forelandward dip presently observed in the autochthon is quite surprising, because in other segments of the Cordillera, such as the Canadian Rockies, the underthrust foreland still preserves an overall west-dipping attitude, inherited from the former Laramide flexure.

Only a few Tmax and Ro data were available in the allochthon due to the lack of organic-rich outcrops. Diagenetic quartz could ultimately be identified in cemented fractures of the carbonate and used as a palaeo-thermo-barometer, because this single mineral turned out to contain both sets of synchronous aqueous and hydrocarbon inclusions.

Unexpectedly, the P–T path derived from isochores documents a few kilometres of unroofing of the Cretaceous carbonate platform, which is best explained by the post-Laramide erosional removal of a similar thickness of Late Cretaceous–Paleocene synflexural flysch (Fig. 12c, d). When projected to its pre-orogenic configuration, assuming an initial horizontal top surface at the onset of the Eocene Laramide thrust emplacement, the restoration of this currently missing flexural sequence in turn requires generation of a coeval space at basin scale to accommodate such sedimentary thickness at the top of the well-known carbonate sequence, which is best explained by assuming an initial west-dipping configuration of the foreland (Fig. 12b).

Use of calcite twins for palaeo-burial reconstructions

For many years calcite twins have been considered among the most common stress–strain markers in fold-and-thrust belts. Calcite twin analyses have been widely used to constrain both the structural and kinematic evolution of thrust belts, but also recently to derive differential stress magnitudes during deformational events. Attention has been particularly focused on the estimates of palaeo-differential stresses at the onset of folding (layer parallel shortening, LPS) and during late stage

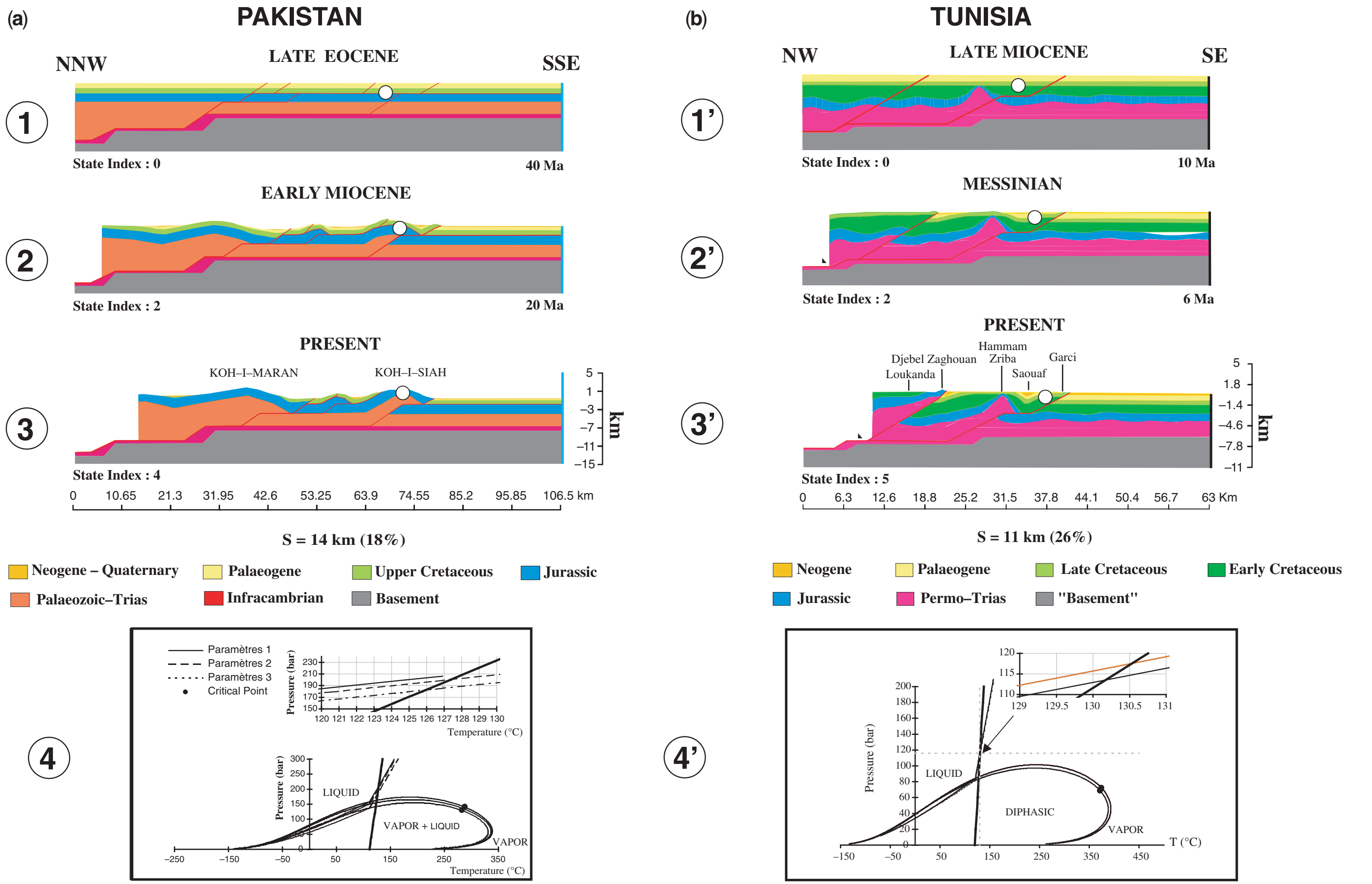

Fig. 11. Cross sections and PVT modelling of Baluchistan and Tunisia (modified after Benchilla *et al.* 2003). Left column = Pakistani case study; Right column = Tunisian case study. In both cases, a kinematic model is provided, including pre-inversion, inversion and present stages. PVT modelling from fluid inclusions in fluorite deposits exposed at the surface (bottom diagrams) indicate these ore deposits developed at the onset of basin inversion, when the host reservoirs where still deeply buried beneath efficient seals.

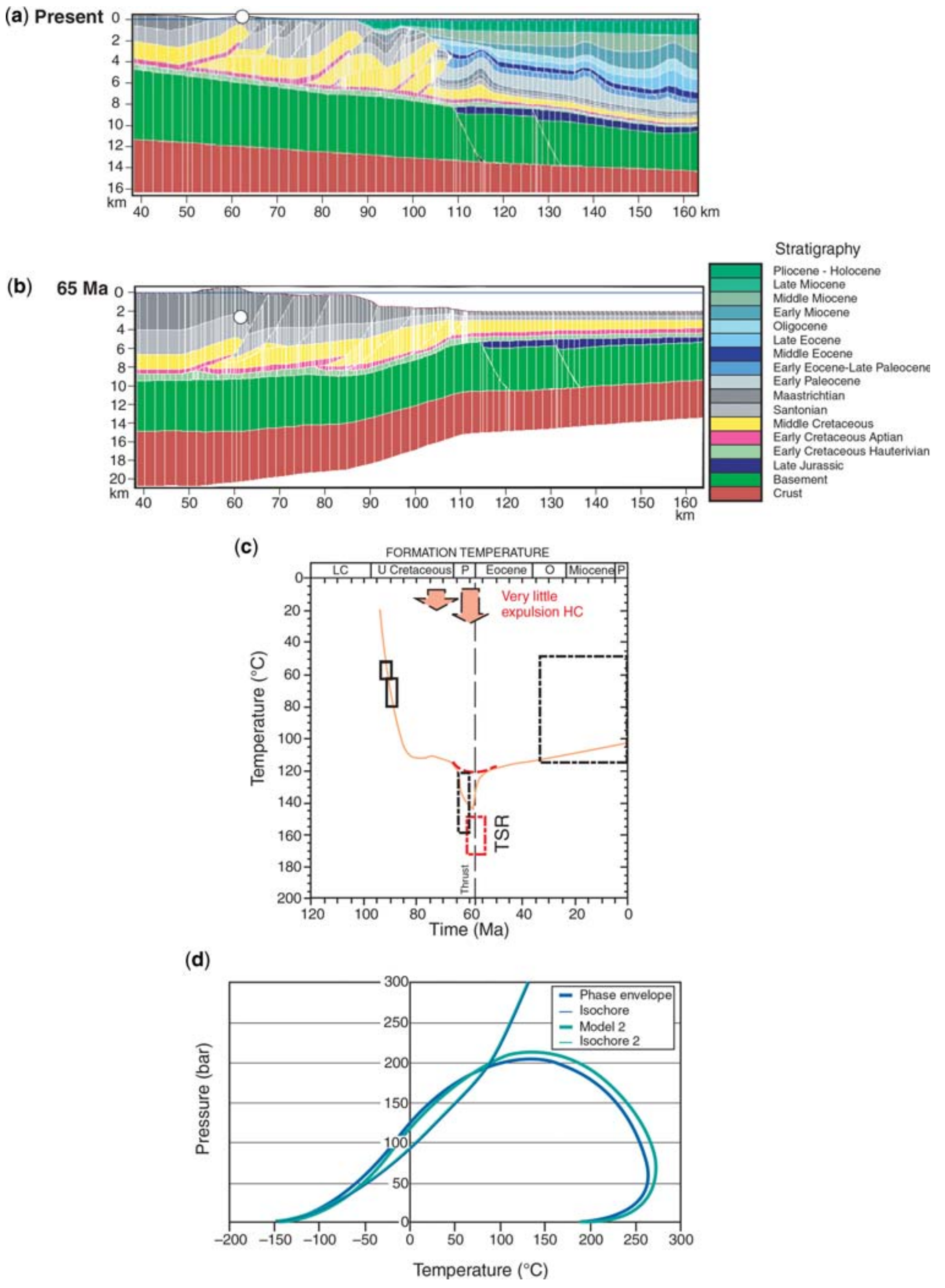

Fig. 12. Fluid inclusions data and PVT modelling as constraints for palaeo-burial reconstructions along a regional transect across the Cordoba Platform (Eastern Mexico; modified after Roure *et al.* 2009*a*; Ferket *et al.* 2003, 2010). (**a**) Top section: Present architecture of the transect, with an east-dipping attitude of the basement. (**b**) Central section: Laramide deformation stage, the basement being restored to accommodate the 4.5 km of Late Cretaceous–Paleocene flexural sequence, which have been subsequently removed by erosion, but are required to account for the PVT modelling of fluid inclusions taken from cements at the top of the Cretaceous platform carbonates in the inner (western) part of the section. (**c**) Burial v. depth plot of Mesozoic carbonates in eroded anticlines (indicated by a white circle in the sections). (**d**) Bottom: results of the PVT modelling on fluid inclusions from Mesozoic carbonates.

fold tightening. An important result is that at the scale of individual structures, differential stresses recorded by rocks were largely dependent on the palaeo-burial before folding and on subsequent erosional history (e.g. Lacombe 2001).

A new method to estimate maximum palaeoburial and subsequent uplift by folding in fold-and-thrust belts, based on calcite twin analysis, has recently been proposed (Lacombe *et al.* 2009). This method basically combines estimates of differential stresses related to LPS with the hypothesis that stress in the upper continental crust is primarily in frictional equilibrium (Townend & Zoback 2000; Lacombe 2007).

In the Albanian foreland taken as a case study (Figs 9 & 13a), calcite twin analysis provides reliable constraints on both the early stages of the tectonic history of the thrust belt, including development of pre-folding vein systems currently observed in folded strata, and on the amount of maximum burial of the Cretaceous foreland rocks during flexural subsidence and on their subsequent uplift during Neogene folding.

Summary of the method for determining of palaeo-stress orientations, differential stress magnitudes and palaeo-burial using inversion of calcite twin data

Mechanical e-twinning readily occurs in calcite deformed at low temperature (Fig. 13b). Calcite twinning requires a low critical resolved shear stress (CRSS) of 10 ± 4 MPa which depends on grain size and internal twinning, and has only a small sensitivity to temperature, strain rate and confining pressure, therefore fulfilling most of the requirements for palaeo-piezometry (Lacombe 2007).

Basically, the principle of the stress inversion technique used herein (Etchecopar 1984; refer to Lacombe 2001 for details) consists of finding the stress tensor that best fits the distribution of twinned and untwinned planes (the latter being those of potential e-twin planes that never experienced a resolved shear stress of sufficient magnitude to cause twinning). The orientations of the principal stresses are calculated, together with the stress ellipsoid shape ratio and the peak differential stress ($\sigma 1-\sigma 3$). It is to date the only technique that computes simultaneously principal stress orientations and differential stress magnitudes from a set of twin data, therefore allowing us to relate unambiguously differential stress magnitudes to a given stress orientation and stress regime. Numerous studies have demonstrated its potential to derive regionally significant stress patterns, even in polyphase tectonics settings (e.g. Lacombe *et al.* 1990; Rocher *et al.* 1996; and references therein).

The hypothesis of crustal frictional stress equilibrium implies uniform stress differences at a given depth and for a given stress regime; regardless of the 'intensity' of deformation, the style of deformation is probably simply a function of the strain rate. The strength of the continental crust down to the brittle–ductile transition is therefore primarily controlled by frictional sliding on well-oriented pre-existing faults, with frictional coefficients of 0.6–0.9 and under hydrostatic fluid pressure (Townend and Zoback 2000). One can therefore draw the curves of differential stress values as a function of depth in a crust in frictional equilibrium for both strike-slip (SS) and reverse faulting (R) stress regimes, with values of λ [$\lambda = P_f/\rho gz$ where Pf is the pore-fluid pressure, ρ the density of the overlying rocks, g the acceleration of gravity and z the depth] of 0.38 (hydrostatic) and 0 (dry) and for friction coefficient μ values of 0.6 and 0.9 (Lacombe 2007, Fig. 13c). Peak differential stress values are estimated from calcite twin analysis, and the principle of the method consists in reporting these values on the above-mentioned curves to derive the probable range of depths at which twinning occurred. If differential stresses are related to LPS that reflects the onset of stress build-up in horizontal strata and was likely recorded at the maximum burial just before the onset of folding, this allows us to infer the probable maximum range of depths at which rock samples recorded LPS twinning strain before becoming uplifted by folding.

Geological setting of the Albanides

The Albanides are a branch of the Alpine orogenic belt, which can be subdivided into an eastern internal zone and a western external zone (Meço & Aliaj 2000; Nieuwland *et al.* 2001). The internal Albanides consist of thick-skinned thrust sheets with ophiolites in the Mirdita Zone (see the section above on the Impact of the Mirdita Ophiolite on the thermicity of footwall strata). The external Albanides comprise the Krasta–Cukali, the Kruja and the Ionian Zones (Velaj *et al.* 1999; Meço & Aliaj 2000) (Fig. 9).

During the Alpine orogeny, the Albanian foothills formed as a consequence of the deformation of the former eastern passive margin of Apulia; the external zones were overthrust during the Neogene (Roure *et al.* 2004). Tectonic loading applied by the hinterland (Mirdita Ophiolite, see above) and westward thrusting of basinal units of the Krasta Zone induced the progressive development of a wide flexural basin, which ultimately impacted the Outer Albanides lithosphere in late Oligocene times. Growth anticlines started to develop in late Oligocene–Aquitanian times in the Ionian Basin. This main episode of shortening ended before

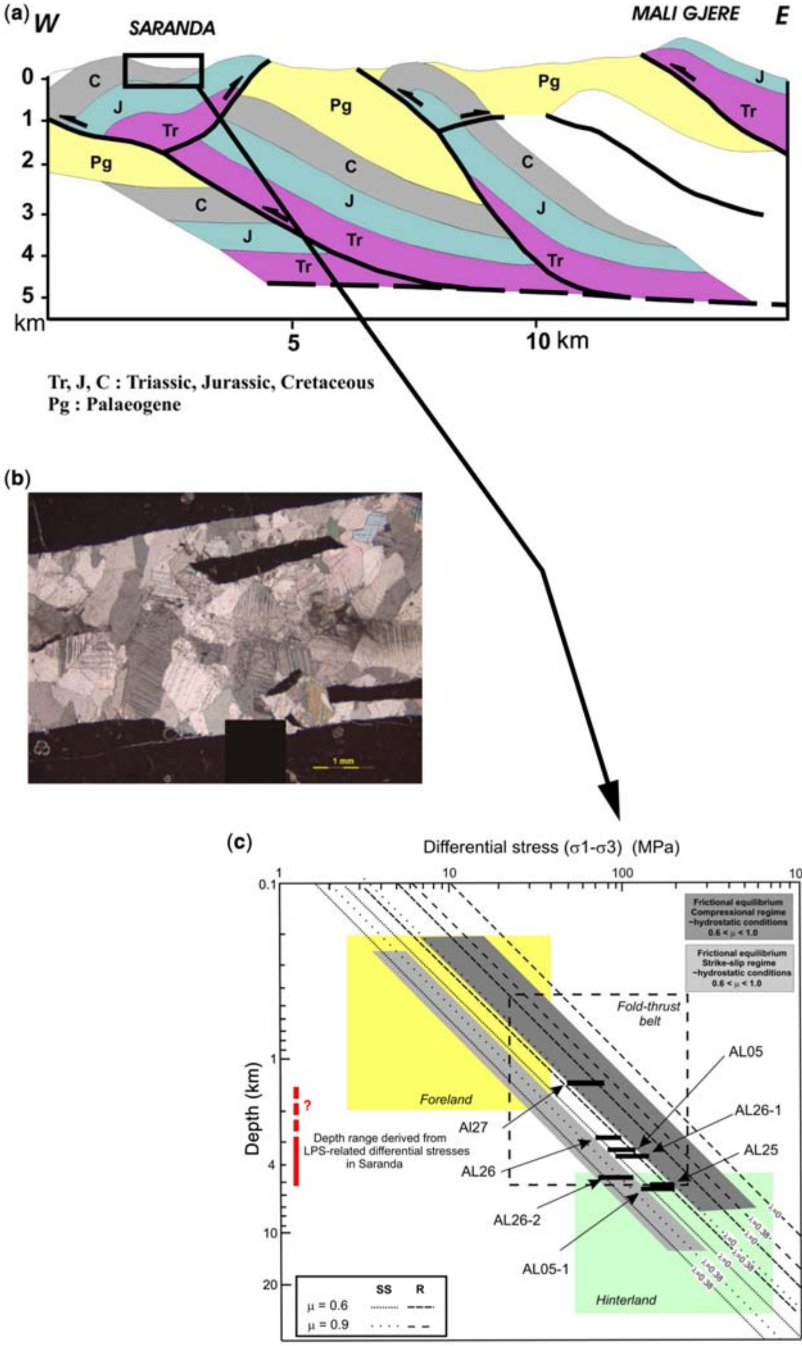

Fig. 13. Use of calcite twins in palaeo-burial reconstructions. (**a**) Geological section across the Saranda anticline (modified after Roure *et al.* 1995; see location in Fig. 9). (**b**) Example of twinned calcite crystal observed in vein. (**c**) LPS-related differential stress values determined from calcite twins reported on stress/depth curves built for a crust in frictional stress equilibrium (Lacombe 2007), and derived palaeo-burial values of Cretaceous limestones in Saranda. Labels 1 and 2 (e.g. AL05-1, AL26-2) refer to stress estimates obtained from subsets of twin data collected in grains of homogeneous sizes, while others were obtained from the whole twin dataset of the sample (for details, refer to Lacombe *et al.* 2009).

deposition of Langhian–Serravallian clastic rocks. Collisional deformation probably reached the outermost parts of the Albanides by early to middle (?) Miocene times. A second episode of tectonic shortening is documented near the Vlora–Elbasan transfer zone and further north in the Peri-Adriatic Depression, where Pliocene out-of-sequence thrusts and backthrusts offset a pre-Messinian erosional surface.

The Saranda anticline is the outermost fold of the southern external Albanides (Figs 9 & 13a). This anticline has an asymmetric structure with a subvertical eastern flank. Two main vein sets were identified in Cretaceous limestones. The first vein set, oriented *c*. N140°, likely developed in response to the flexure of the foreland in front of the advancing thrust sheets, contemporary with burial and possibly under high fluid pressures (Lacombe *et al.* 2009). The second set (II), oriented *c*. N060°, is closely associated with LPS stylolites and marks the trend of the regional compression. Advantage has been taken of the widespread occurrence of these pre-folding vein sets to collect calcite twin data (Fig. 13b) and to characterize stress orientations and differential stress magnitudes related to LPS.

Palaeo-stresses and palaeo-burial in the Saranda anticline

Calcite twinning from vein sets consistently recorded pre-folding, NE–SW-directed regional compression. Since LPS reflects the onset of stress build-up in horizontal strata, LPS-related twin strain was recorded at the maximum burial just before the onset of folding. As a result, reporting differential stress magnitudes on the stress–depth curves (Fig. 13c) reveals that in Saranda, the maximum burial of the Cretaceous limestones was about 1.5–5 km, with a mean weighted value of around 4 $\pm$ 1 km (Fig. 13c). This *c*. 4 km maximum palaeo-burial value is consistent with independent palaeo-burial estimates from stratigraphy, maturity rank of organic matter, palaeo-temperature/palaeo-geothermal gradients from fluid inclusions and predictions of kinematic modelling of the Albanian foreland (Lacombe *et al.* 2009).

Conclusions

The new method for estimating maximum palaeo-burial and subsequent uplift by folding in fold-and-thrust belts, based on calcite twin analysis, basically combines estimates of LPS-related differential stresses with the hypothesis that crustal stress is in frictional equilibrium. The limits of this approach have been discussed in Lacombe *et al.* (2009). Palaeo-depth values inferred from LPS-related differential stresses yield an upper bound for burial and constrain the amount of subsequent exhumation/vertical movement. Palaeo-burial estimates from post-folding stress tensors may place additional constraints on the depth of rocks when folding ended, and, therefore, on the exhumation path of these rocks toward the surface. A major interest of this method is that it can potentially be carried out in any fold and thrust belt where twinned calcite occurs. In the absence of other palaeo-depth indicators, this method will provide valuable constraints on the amount of burial of foreland rocks during flexural subsidence and of their subsequent uplift during folding, thus leading to a better quantification of vertical movements in forelands, even where subsurface data are not sufficient to build a well-constrained geological section (e.g. Saranda).

A way to reduce the range of uncertainties on palaeo-stress/palaeo-burial estimates is to combine calcite twinning palaeo-piezometry with the systematic analysis of fluid inclusions, which allows derivation of the pore pressure from the fluid density or inference of the value of the vertical stress assuming hydrostatic conditions (see section above on Use of hydrocarbon-bearing fluid inclusions in palaeo-burial reconstructions). Estimates of palaeo-burial and, therefore, of palaeo-depth of deformation in fold-and-thrust belts from calcite twins should therefore be combined in the future with the systematic use of palaeo-thermometers such as vitrinite reflectance, illite crystallinity, or fluid (mixed hydrocarbon/aqueous) inclusions coupled with numerical modelling of the thermal evolution of tectonic units.

Overall conclusions

Major errors can be made in predicting the palaeo-burial, thermicity and hydrocarbon potential of foothill areas if the rates and amounts of erosion cannot be properly estimated, and when major lateral changes in crustal/lithospheric thicknesses occurred in the foreland and in the hinterland during either the initial, passive margin episodes, or younger post-orogenic stages of slab detachment and asthenospheric rise.

Conversely, fission track data, fluid inclusions micro-thermometry, magnetic fabric, diagenetic studies and calcite twin analyses become increasingly useful for petroleum exploration when moving from passive margins and foreland basins, where sedimentary burial is more or less continuous, toward foreland fold and thrust belts, where large amounts of sometimes localized erosion occurred. In such settings, more analytical work becomes required to decrease the error bars during basin modelling.

In the future, pioneer analytical techniques such as the ‘clumped isotopes’ or $\Delta47$ (based on the molecular combination of the isotopes of ^{13}C and ^{18}O in the CO_2 molecule which occur at masses 47 to 49; Eiler 2007) and Raman spectrometry of the organic matter are likely to provide other sensitive palaeothermometers for a range of temperatures of direct interest for sedimentary basins. Whereas clumped isotope geochemistry is likely to measure the temperature of crystallization of calcite and dolomite cements when lower than 120 °C, provided no further burial increase occurred (Ghosh *et al.* 2006, 2007; Eiler 2007), HRTM (High-Resolution Transmission Electro-Microscopy) and Raman micro-spectrometry can be used for ranking the organic matter evolution between 330 and 650 °C (Beyssac *et al.* 2002; Lahfid 2008; Lahfid *et al.* 2008).

Most case studies developed in this paper have shown that the same overall dewatering processes known from offshore accretionary wedges still operate in FTB (i.e. squeegee episodes of tectonically induced fluid flow associated with tectonic compaction and pressure-solution mechanisms). These LPS episodes thus dramatically control the overall reservoir quality in both carbonate and sandstone units of the allochthon as well as the underthrust foreland. In contrast, gravitational (topography-driven) fluid flow does not have much impact on the fluid flow history of most productive reservoirs, except for tar belts such as the Athabasca sandstones (Alberta) and Orinoco belt in Venezuela (Faja Petrolifera), and possibly also in Papua New Guinea, known for its very active hydrodynamic regime, because hydrocarbon accumulations are usually mostly confined beneath the regional permeability barriers developing during the flexural evolution of the foreland.

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References

ALBPETROL. 1995. Recent developments in exploration and oil production and the future in the free market economy. 1965–1995 – 30 years Oil and Gas Institute, 23–26.

Aubourg, C. 1999. *Une utilisation structurale de la fabrique magnétique*. Thèse d'Habilitation à Diriger des Recherches, HDR, Univ. of Cergy-Pontoise, France, 67.

Aubourg, C., Frizon De Lamotte, D., Poisson, A. & Mercier, E. 1997. Magnetic fabric and oblique ramp-related folding: a case study from the Western Taurus (Turkey). *Journal of Structural Geology*, **8**, 1111–1120.

Averbuch, O., Frizon De Lamotte, D. & Kissel, C. 1992. Magnetic fabric as a structural indicator of the deformation path within fold–thrust structures: a test case from the Corbières (NE Pyrenees, France). *Journal of Structural Geology*, **14**, 461–474.

Bachu, S. 1999. Flow systems in the Alberta Basin: patterns, types and driving mechanisms. *Bulletin of Canadian Petroleum Geology*, **47**, 455–474.

Benchilla, L., Guilhaumou, N., Mougin, P., Jaswal, T. & Roure, F. 2003. Paleoburial and pore pressure reconstruction of reservoir rocks in foothills areas: a sensitivity test in the Hammam Zriba (Tunisia) and Koh-I-Maran (Pakistan) ore deposits. *Geofluids*, **3**, 103–123.

Beyssac, O., Rouzaud, J. N., Goffé, B., Brunet, F. & Chopin, C. 2002. Graphitization in high-pressure, low-temperature metamorphic gradient: a HRTEM and Raman microspectroscopy study. *Contributions to Mineralogy and Petrology*, **143**, 19–31.

Bordas-Le Floch, N. 1999. *Diagenèse, compaction et déformation des réservoirs gréseux dans les chaînes plissées*. PhD thesis, Univ. Paris VI, 298.

Burbank, D. W. 1983. The chronology of intermontane basin development in the Northwestern Himalaya and the evolution of the Northwest Syntaxis. *Earth and Planetary Science Letters*, **64**, 77–92.

Burbank, D. W. & Beck, R. A. 1989. Early Pliocene uplift of the Salt Range: temporal constraints on thrust wedge development, Northwest Himalaya, Pakistan. *In*: Malinconico, L. L. & Lillie, R. T. (eds) *Tectonics of the Western Himalaya*. GSA Special Paper, **232**, 112–129.

Burbank, D. W. & Johnson, G. D. 1982. Intermontane basin development in the past 4 Myr in the Northwest Himalaya. *Nature*, **298**, 432–436.

Carminati, E., Doglioni, C. *et al.* 2004. TRANSMED, Transect III: a lithosphere cross section through the Central and Eastern Mediterranean region. *In*: Cavazza, W., Roure, F., Spakman, W., Stampfli, G. M. & Ziegler, P. A. (eds) *The TRANSMED Atlas, The Mediterranean Region from Crust to Mantle*. Springer-Verlag, Berlin, 141+CD-ROM.

Casero, P., Roure, F. & Vially, R. 1991. Tectonic framework and petroleum potential of the southern Apennines. *In*: Spencer, A. (ed.) *Generation, accumulation and production of Europe's hydrocarbons*. European Association of Petroleum Geologists, Berlin meeting, Oxford University Press, Oxford, 381–387.

Cavazza, W., Ziegler, P., Spakman, W., Stampfi, & Roure, F. (eds) 2004. *The TRANSMED Atlas: The Mediterranean Region from Crust to Mantle*. Springer-Verlag, Heidelberg, 141+CD-ROM.

Cobbold, P. R., Mourgues, R. & Boyd, K. 2004. Mechanism of thin-skinned detachment in the Amazon fan: assessing the importance of fluid overpressures and hydrocarbon generation. *Marine and Petroleum Geology*, **21**, 1013–1025.

Collaku, A., Cadet, J. P., Melo, V. & Bonneau, M. 1990. Sur l'allochtonie des unités albanaises: mise en évidence de fenêtres tectoniques à l'arrière de la nappe ophiolitique de la Mirdita (Albanie). *Comptes Rendus Académie des Sciences (Paris)*, **311**, 1251–1258.

Deville, E. & Sassi, W. 2006. Contrasting thermal evolution of thrust systems: an analytical and modelling approach in the front of the Western Alps. *American Association of Petroleum Geologists Bulletin*, **90**, 887–907.

De Wever, B. 2008. *Diagenesis and fluid flow in the Sicilian fold-and-thrust belt*. PhD Thesis, KU-Leuven, 184.

Durham, L. 2008. Tupi: find of the year. Salt couldn't hide elephant from explorer. *American Association of Petroleum Geologists Explorer*. January 2008.

Eiler, J. M. 2007. 'Clumped-isotope' geochemistry: the study of naturally-occurring multiply-substituted isotopologues. *Earth and Planetary Science Letters*, **262**, 309–327.

Etchecopar, A. 1984. *Etude des états de contraintes en tectonique cassante et simulation de déformations plastiques (approche mathématique)*. PhD thesis, Doctorat-ès-Sciences, Univ. Sciences et Techniques du Languedoc, Montpellier, 270.

Evans, M. A., Lewchuk, M. T. & Elmore, R. D. 2003. Strain partitioning of deformation mechanism in limestones: examining the relationship of strain and anisotropy of magnetic susceptibility (AMS). *Journal of Structural Geology*, **25**, 1525–1549.

Faure, J. L., Osadetz, K., Benaouali, N., Schneider, F. & Roure, F. 2004. Kinematic and petroleum modelling of the Alberta Foothills and adjacent foreland, west of Calgary. *Oil and Gas Science and Technology, Revue de l'IFP*, **1**, 81–108.

Ferket, H., Ortuño, S., Swennen, R. & Roure, F. 2003. Diagenesis and fluid flow history in reservoir carbonates of the Cordilleran fold- and thrust- belt: The Cordoba Platform. *In*: Bartolini, C., Burke, K., Buffler, R., Blickwede, J. & Burkart, B. (eds) *Mexico and the Caribbean Region: Plate Tectonics, Basin Formation and Hydrocarbon Habitats*. American Association of Petroleum Geologists, Memoir, **79**, Chapter 10, 283–304.

Ferket, H., Swennen, R., Ortuño-Arzate, S., Cacas, M. C. & Roure, F. 2004. Hydrofracturing in the Laramide foreland fold-and-thrust belt of Eastern Mexico. *In*: Swennen, R., Roure, F. & Granath, J. (eds) *Deformation, Fluid Flow and Reservoir Appraisal in Foreland Fold-and-Thrust Belts. American Association of Petroleum Geologists*, Hedberg Series (Memoir), **1**, 133–156.

Ferket, H., Guilhaumou, N., Roure, F. & Swennen, R. 2010. Fluid inclusions, thermal and PVT modelling: key to validate a kinematic model and constrain palaeo-geothermal gradients for the Cordoba petroleum system (NE Mexico). *Marine and Petroleum Geology*, in press.

Fermor, P. R. & Moffat, I. W. 1992. Tectonics and structure of the Western Canada foreland basin. *In*: Macqueen, R. W. & Leckie, D. A. (eds) *Foreland Basins and Fold Belts.* American Association of Petroleum Geologists Memoir, **55**, 81–105.

Frizon De Lamotte, D., Mercier, E., Dupré-La Tour, A., Robion, P. & Averbuch, O. 1997. Cinématique du plissement et déformation interne des roches: l'exemple du pli de Lagrasse (Aude, France). *Comptes Rendus de l'Académie des Sciences, Paris*, **32**, IIa, 591–598.

Frizon De Lamotte, D., Souque, C., Grelaud, S. & Robion, P. 2002. Early record of tectonic magnetic fabric during inversion of a sedimentary basin: short review and examples from the Corbières transfer zone (France). *Bulletin de la Société Géologique de France*, **173**, 461–469.

Ge, S. & Garven, G. 1989. Tectonically induced transient groundwater flow in foreland basins. *In*: Price, R. A. (ed.) *The Origin and Evolution of Sedimentary Basins and their Energy and Mineral Resources*. AGU, Geophysical Monograph Series, **48**, 145–147.

Ge, S. & Garven, G. 1994. A theoretical model for thrust-induced deep groundwater expulsion with application to the Canadian Rocky Mountains. *Journal of Geophysical Research, B, Solid Earth and Planets*, **99**, 13851–13868.

Ghosh, P., Adkins, H., Balta, B., Guo, W., Schauble, E. A., Schrag, D. & Eiler, J. M. 2006. ^{13}C–^{18}O bonds in carbonate minerals: a new kind of paleothermometer. *Geochimica et Cosmochimica Acta*, **70**, 1439–1456.

Ghosh, P., Eiler, J., Campana, S. E. & Freeney, E. F. 2007. Calibration of the carbonate 'Clumped isotope' paleothermometer for otoliths. *Geochimica et Cosmochimica Acta*, **71**, 2736–2744.

Granjeon, D. & Joseph, P. 1999. Concepts and application of a 3D multiple lithology, diffusive model in stratigraphic modelling. *In*: Harbough, J. W. *et al.* (eds) *Numerical Experiments in Stratigraphy*. SEPM, Special Publication, **62**, 197–210.

Grelaud, S., Sassi, W., Frizon De Lamotte, D., Jaswal, T. & Roure, F. 2002. Kinematics of eastern Salt Range and South Potwar Basin (Pakistan). A new scenario. *Marine and Petroleum Geology*, **19**, 1127–1139.

Guilhaumou, N. & Dumas, P. 2005. Synchrotron FTIR hydrocarbon fluid inclusions microanalysis applied to diagenetic history and fluid flow reconstruction in reservoir appraisal. *Oil and Gas Science Technology, Revue de l'IFP*, **60**, 1–12.

Guilhaumou, N., Larroque, C., Nicot, E., Roure, F. & Stephan, J. F. 1994. Mineralized veins resulting from fluid flow in decollement zones of the Sicilian prism: evidence from fluid inclusions. *Bulletin de la Société Géologique de France*, **165**, 425–436.

Guilhaumou, N., Ellouz, N., Jaswal, T. & Mougin, P. 2000. Genesis and evolution of hydrocarbon entrapped in fluorite deposits of Koh-i-Maran (North Kirthar Range, Pakistan). *Marine and Petroleum Geology*, **17**, 1151–1164.

Guilhaumou, N., Benchilla, L., Mougin, P. & Dumas, P. 2004. Advances in hydrocarbon fluid inclusions microanalysis and PVT modelling: Diagenetic history, P–T and fluid flow reconstruction, a case study in the North Potwar Basin, Pakistan. *In*: Swennen, R., Roure, F. & Granath, J. (eds) *Deformation, Fluid Flow and Reservoir Appraisal in Foreland Fold-and-Thrust Belts.* American Association of Petroleum Geologists, Hedberg Series, **1**, 5–20.

Hardebol, N. J., Callot, J. P., Faure, J. L., Bertotti, G. & Roure, F. 2007. Kinematics of the SE Canadian foreland fold and thrust belt: implications for the thermal and organic maturation history. *In*: Lacombe, O., Lavé, J., Roure, F. & Vergés, J. (eds) *Thrust Belts and Foreland Basins*. New Frontiers in Earth Sciences, Springer, Berlin, 179–202.

Hardebol, N., Callot, J. P., Bertotti, J. L. & Faure, J. L. 2009. Sedimentary and tectonic burial history appraisal and consequent temperature and organic maturation evolution in thrust-belt systems: a study on the SE Canadian Cordillera. *Tectonics*, **28**, TC3003, doi: 10.1029/2008TC002.

Hippolyte, J. C., Angelier, J. & Roure, F. 1996. Paleostress analyses and fold-and-thrust belt kinematics in the Southern Apennines. *In*: Roure, F., Ellouz, N., Shein, V. S. & Skvortsov, I. I. (eds) *Geodynamic Evolution of Sedimentary Basins*. Edition Technip, 157–169.

Lacombe, O. 2001. Paleostress magnitudes associated with development of mountain belts: insights from tectonic analyses of calcite twins in the Taiwan Foothills. *Tectonics*, **20**, 834–849.

Lacombe, O. 2007. Comparison of paleostress magnitudes from calcite twins with contemporary stress magnitudes and frictional sliding criteria in the continental crust: mechanical implications. *Journal of Structural Geology*, **29**, 86–99.

Lacombe, O., Angelier, J., Laurent, P., Bergerat, F. & Tourneret, C. 1990. Joint analyses of calcite twins and fault slips as a key for deciphering polyphase tectonics: Burgundy as a case study. *Tectonophysics* **182**, 279–300.

Lacombe, O., Malandain, J., Vilassi, N., Amrouch, K. & Roure, F. 2009. From paleostress to paleoburial in fold–thrust belts: preliminary results from calcite twin analysis in the Outer Albanides. *In*: Bertotti, G., Frizon de Lamotte, D., Teixell, A. & Charroud, H. (eds) *The Geology of Vertical Movements*. Tectonophysics, **475**, 128–141, doi: 10.1016/j.tecto.2008.10.023.

Lahfid, A. 2008. *Géothermomètres dans des séries argileuses très matures*. PhD Thesis, ENS, Paris.

Lahfid, A., Beyssac, O., Deville, E. & Goffé, B. 2008. A new method to estimate paleotemperatures in deep petroleum basins: the use of RSCM geothermometer. Abstract EGU, General Assembly, A09484.

Larroque, C., Guilhaumou, N., Stéphan, J. F. & Roure, F. 1996. Advection of fluids at the front of the Sicilian Neogene subduction complex. *Tectonophysics*, **254**, 41–55.

Machel, H. G. & Cavell, P. A. 1999. Low-flux, tectonically-induced squeegee fluid flow (‘hot flash’) into the Rocky Mountain foreland basin. *Bulletin of Canadian Petrological Geology*, **47**, 510–533.

Mattei, M., Sagnotti, L., Faccenna, C. & Funiciello, R. 1997. Magnetic fabric of weakly deformed clay-rich sediments in Italian Peninsula: relationship with compressional and extensional tectonics. *Tectonophysics*, **271**, 107–122.

Meço, S. & Aliaj, S. 2000. *Geology of Albania*. Gebrüder Borntraeger, Berlin, 246.

Mosca, F., Sciamanna, S., Sassi, W., Rudkiewicz, J. L. & Gambini, R. 2004. Predicting hydrocarbon generation and expulsion in the Southern Apennines thrust belt by 2-D integrated structural and geochemical modelling. Part II – Geochemical modelling. *In*: Swennen, R., Roure, F. & Granath, J. (eds) *Deformation, Fluid Flow and Reservoir Appraisal in Foreland Fold and Thrust Belts*. American Association of Petroleum Geologists, Hedberg Memoir, **1**, 69–78.

Muceku, B., Mascle, G. H. & Tashko, A. 2007. First results of fission-track thermochronology in the Albanides. *Geological Society, London, Special Publications*, **260**, 539–556.

Nieuwland, D. A., Urai, J. & Knoop, M. 2000. In-situ stress measurements in model experiments of tectonic faulting. *In*: Lehner, F. & Urai, J. (eds) *Aspects of Tectonic Faulting*. Springer Verlag, Berlin, Heidelberg, New York, 155–167.

Nieuwland, D. A., Oudmayer, B. C. & Valbona, U. 2001. The tectonic development of Albania: explanation and prediction of structural styles. *Marine and Petrological Geology*, **18**, 161–177.

O’Brien, J. J. & Lerche, I. 1987. Heat flow and thermal maturation near salt diapirs. *In*: Lerche, I. & O’Brien, J. J. (eds) *Dynamical Geology of Salt and Related Structures*. Academic Press, San Diego, 711–751.

Robion, P., Faure, J. L. & Swennen, R. 2004. Late Cretaceous chemical remagnetization of the Palaeozoic carbonates from the undeformed foreland of the Western Canadian Cordillera. *In*: Swennen, R., Roure, F. & Granath, J. (eds) *Deformation, Fluid Flow and Reservoir Appraisal in Foreland Fold-and-Thrust Belts*. American Association of Petroleum Geologists, Hedberg Series, **1**, 317–330.

Rocher, M., Lacombe, O., Angelier, J. & Chen, H. W. 1996. Mechanical twin sets in calcite as markers of recent collisional events in a fold-and-thrust belt: evidence from the reefal limestones of southwestern Taiwan. *Tectonics* **15**, 984–996.

Roedder, E. 1984. Fluid inclusions. *Reviews in Mineralogy, Mineralogical Society of America*, **12**.

Roure, F. 2008. Foreland and hinterland basins: what is controlling their evolution? Alpine Workshop, Davos Proceedings, *Swiss Journal of Geosciences*, **101**, 5–29, doi: 10.1007/s00015-008-1285-x.

Roure, F. & Sassi, W. 1995. Kinematics of deformation and petroleum system appraisal in Neogene foreland fold-and-thrust belts. *Petroleum Geoscience*, **1**, 253–269.

Roure, F., Prenjasi, A. & Xhafa, Z. 1995. Petroleum geology of the Albanian foothills. American Association of Petroleum Geologists, Nice, post-conference fieldtrip guide-book, 100.

Roure, F., Bordas-Lefloch, N. *et al.* 2003. Petroleum systems and reservoir appraisal in the Subandean basins (eastern Venezuela and eastern Colombian foothills). *In*: Bartolini, C., Burke, K., Buffler, R., Blickwede, J. & Burkart, B. (eds) *Mexico and the Caribbean Region: Plate Tectonics, Basin Formation and Hydrocarbon Habitats*. American Association of Petroleum Geologists, Memoir, **79** (Chapter 34).

Roure, F., Nazaj, S., Mushka, K., Fili, I., Cadet, J. P. & Bonneau, M. 2004. Kinematic evolution and petroleum systems: an appraisal of the Outer Albanides. *In*: McKlay, K. (ed.) *Thrust Tectonics and Hydrocarbon Systems*. American Association of Petroleum Geologists, Memoir, **82**, Chapter 24, 474–493.

Roure, F., Faure, J. L., Colletta, B., Macellari, C. & Osorio, M. 2005*a*. Structural evolution and coupled kinematic-thermal modelling of the Upper Magdalena Basin in the vicinity of the Garzon Massif, Colombia. *American Association of Petroleum Geologists, Calgary*, Abstract Annual Meeting, June 16–19, Abst. 90039.

Roure, F., Swennen, R. *et al.* 2005*b*. Incidence and importance of tectonics and natural fluid migration on reservoir evolution in foreland fold-and-thrust belts. *In*: Brosse, E *et al.* (eds) *Oil and Gas Science and Technology-Revue de l'IFP*, **60**, 67–106.

Roure, F., Alzaga, H. *et al.* 2009*a*. Long lasting interactions between tectonic loading, unroofing, postrift thermal subsidence and sedimentary transfer along the Western margin of the Gulf of Mexico: Some insights from integrated quantitative studies. *In*: Bertotti, G., Frizon de Lamotte, D. & Teixell, A. (eds) *Tectonics of Vertical Movements*, Special Issue, Tectonophysics, in press.

Roure, F., Cloetingh, S., Scheck-Wenderoth, M. & Ziegler, P. 2009*b*. Achievements and challenges in sedimentary basins dynamics. *In*: Cloetingh, S. & Negendank, J. (eds) *New Frontiers in Integrated Solid Earth Sciences*. Springer, 145–233.

Saint-Bezar, B., Hébert, R. L., Aubourg, C., Robion, P., Swennen, R. & Frizon De Lamotte, D. 2002. Magnetic fabric and petrographic investigation of hematite-bearing sandstones within ramp-related folds: examples from the South Atlas front (Morocco). *Journal of Structural Geology*, **24**, 1507–1520.

Sassi, W. & Rudkiewicz, J. L. 2000. Computer modelling of petroleum systems along regional cross-sections in foreland fold-and-thrust belts. EAGE Conference, Malta 2000, extended abstract.

Schneider, F. 2003. Basin modelling in complex area: examples from eastern Venezuelan and Canadian foothills. *Oil and Gas Science and Technology, Revue de l'IFP*, **58**, 313–324.

Schneider, F., Devoitine, H., Faille, I., Flauraud, E. & Willien, F. 2002. Ceres2D: a numerical prototype for HC potential evolution in complex areas. *Oil and Gas Science and Technology, Revue de l'IFP*, **57**, 607–619.

Sciamanna, S., Sassi, W., Gambini, R., Rudkiewicz, J. L., Mosca, F. & Nicolai, C. 2004. Predicting hydrocarbon generation and expulsion in the Southern Apennines thrust belt by 2-D integrated structural and geochemical modelling. Part I- Structural and thermal evolution. *In*: Swennen, R., Roure, F. & Granath, J. (eds) *Deformation, Fluid Flow and Reservoir Appraisal in Foreland Fold and Thrust Belts*. American Association of Petroleum Geologists, Hedberg Series, **1**, 51–68.

Smith, T. 2008. Salt's effect on petroleum systems. *Geo Expro*. Website: www.geoexpro.com/geoscience/salt

Summa, L. L., Goodman, E. D., Richardson, M., Norton, I. O. & Green, A. R. 2003. Hydrocarbon systems of Northeastern Venezuela: plate through molecular-scale analysis of the genesis and evolution of the Eastern Venezuela Basin. *Marine and Petroleum Geology*, **20**, 323–349.

Swennen, R., Roure, F. & Granath, J. (eds) 2004. Deformation, fluid flow and reservoir appraisal in foreland fold and thrust belts. *American Association of Petroleum Geologists*, Hedberg Series, **1**, 430.

Teyssier, C., Ferré, E., Whitney, D. L., Norlander, B., Vanderhaeghe, O. & Parkinson, D. 2005. Flow of partially molten crust and origin of extensional detachments during collapse of the Cordilleran orogen. *In*: Bruhn, D. & Burlini, L. (eds) *High Strain Zones Structure and Physical Properties*. Geological Society, London, Special Publication, **254**, 39–64.

Thiery, R. 2006. Thermodynamic modelling of aqueous CH_4-bearing fluid inclusions trapped in hydrocarbon rich environments. *Chemical Geology*, **227**, 154–164.

Townend, J. & Zoback, M. D. 2000. How faulting keeps the crust strong. *Geology*, **28**, 399–394.

Travé, A., Labaume, P. & Vergés, J. 2007. Fluid systems in foreland fold-and-thrust belts: an overview from the Southern Pyrénées. *In*: Lacombe, O., Lavé, J., Roure, F. & Vergés, J. (eds) *Thrust Belts and Foreland Basins*. Frontiers in Earth Sciences, Springer, 93–116.

Van Der Wiel, A. M. 1991. *Uplift and volcanism of the SE Colombian Andes in relation to Neogene sedimentation of the Upper Magdalena Valley*. PhD thesis, Wageningen, the Netherlands, 208.

Van Der Wiel, A. M. & Andriessen, P. 1991. Precambrian to Recent thermotectonic history of the Garzon Massif (Eastern Cordillera of the Colombian Andes) as revealed by fission track analysis. *In*: van der Wiel, A. M. (ed.) *Uplift and Volcanism of the SE Colombian Andes in Relation to Neogene Sedimentation of the Upper Magdalena Valley*. PhD Thesis, Wageningen, the Netherlands.

Vanderhaeghe, O., Medvedev, S., Fullsack, P., Beaumont, C. & Jamieson, R. A. 2003. Evolution of orogenic wedges and continental plateaus: insights from thermal–mechanical models with subduction basal boundary conditions. *Geophysical Journal International*, **153**, 1–25.

Velaj, T., Davison, I., Serjani, A. & Alsop, I. 1999. Thrust tectonics and the role of evaporites in the Ionian Zone of the Albanides. *American Association of Petroleum Geologists Bulletin*, **83**, 1408–1425.

Vilasi, N., Malandain, J. *et al.* 2009. From outcrop and petrographic studies to basin-scale fluid flow modelling: the use of the Albanian natural laboratory for carbonate reservoir characterization. *In*: Cloetingh, S. A. P. L., Ziegler, P. A. & Bogaard, P. J. F. *et al.* (eds) *TOPO-EUROPE: The Geoscience of Coupled Deep Earth-Surface Processes*. Tectonophysics, **474**, 367–392, doi: 10.1016/j.tecto.2009.01.033.

Vrolijk, P. 1987. Tectonically driven fluid-flow in the Kodiak accretionary complex, Alaska. *Geology*, **15**, 466–469.

Zeilinger, G., Seward, D. & Burg, J. P. 2007. Exhumation across the Indus Suture Zone: a record of back sliding of the hanging wall. *Terra Nova*, **9**, 425–431.